

Metrology for Bits and Qubits in Meters: Operational Standards, State-Space Geometry, and Traceable Calibration Chains

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Information is usually treated as abstract: bits flip, qubits rotate, and “distance” between states is spoken of metaphorically. Yet modern science and engineering increasingly demand that information be rendered operationally measurable, traceable, and comparable across platforms. This paper proposes an explicit metrology for bits and qubits in SI units, with a focus on defining distance in meters without confusing physical space with Hilbert space. We develop two complementary standards. The first is a meter-realized approach in which a classical bit is encoded as a calibrated path-length difference in an interferometric device, traceable to an atomic-clock-referenced optical frequency. The second is a state-space approach in which qubit separation is defined by experimentally measurable distinguishability, expressed as an angle on the Bloch sphere, and then mapped into meters through a calibrated phase-to-length conversion. Together these standards separate what can be physically realized and audited from what is merely conventional, clarifying why Planck-scale distances are meaningful as theory but fail as laboratory metrology. The result is a practical blueprint for “information-as-measurable-geometry” that supports reproducible experiments, cross-lab interoperability, and clearer claims at the boundary between quantum information and fundamental physics.

Keywords: bit metrology, qubit metrology, SI traceability, calibration chain, optical frequency standard, interferometer, path length encoding, time-bin qubit, phase metrology, Bloch sphere, Fubini-Study distance, quantum state distinguishability, state-space geometry, phase-to-length conversion, uncertainty budget, quantum tomography, operational definition, information geometry, quantum standards, metrological traceability.

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1. Introduction: Why Information Needs Metrology

Information theory began with an intentional abstraction: a bit is a symbol that can be copied, flipped, or erased, and a qubit is a state vector that can be rotated, entangled, or measured. That abstraction is precisely what made the field universal. Yet the modern landscape has changed. Bits now travel through calibrated optical links that must meet contractual latency budgets. Qubits now ride in hardware stacks whose performance is reported as “fidelity,” “phase noise,” “coherence time,” and “error per gate,” often across laboratories and vendors that cannot share identical devices. In this environment, the most damaging ambiguity is no longer philosophical; it is operational. Researchers casually speak of “distance between states” as if it were self-evident, while engineers and metrologists require that any distance be tied to an instrument, a calibration chain, and an uncertainty budget. The central claim of this paper is simple: if we want information-bearing systems to be comparable, auditable, and interoperable, we need an explicit metrology for bits and qubits—one that tells us what is physically realized, what is merely mapped, and what claims exceed what can be calibrated.

1.1 From abstract symbols to operational standards

A symbol becomes a standard when it can be reproduced by strangers. In metrology, the goal is not merely to define quantities, but to provide a method by which independent laboratories can realize those quantities and quantify their uncertainty. The history of measurement is the history of making abstractions tangible: time becomes a frequency standard; length becomes an optical wavelength; mass becomes a traceable artifact and then, more recently, a constant-based realization. Information is undergoing a similar transition. What once lived entirely in logical operations and paper proofs now lives in physical devices: a “0” is a voltage level, a photon path, a magnetization direction, a charge configuration, or a stable attractor in a nonlinear circuit; a “1” is the complementary state, ideally with known separation and known readout error.

This paper treats that transition as the motivation for a concrete question: if we say “this device stores a bit” or “this apparatus implements a qubit,” what exactly is the physically testable statement being made? The answer cannot be “it behaves like a bit in my circuit diagram.” It must be something like: there exist two operationally distinguishable states, a controlled preparation procedure, a readout procedure, and a stability envelope over time and environment. In this sense, metrology is not an afterthought; it is the bridge between the abstract object (bit/qubit) and the real artifact (hardware that must be calibrated, shipped, replicated, and compared).

In particular, the phrase “distance between states” needs discipline. In classical digital systems, “distance” can often be treated informally because thresholds are forgiving and engineering

margins are large. In quantum systems, “distance” is already a rigorous concept in state space (as distinguishability), but it is rarely tied to SI traceability in a way that permits cross-lab calibration. The move proposed here is to be explicit: define a bit in meters through a meter-realized encoding (path-length difference), and define a qubit distance first in state space (distinguishability), then map it into meters through a calibrated phase-to-length conversion. The aim is not to force everything into “meters” for aesthetic reasons, but to make “distance” auditable and reproducible in the language of measurement.

1.2 The metrology problem: distinguishing convention from realizable measurement

The core metrology problem is that we can always assign numbers, but we cannot always realize them. It is trivially easy to define a mapping that declares some abstract separation to be “one meter,” or “one Planck length,” or “zero meters.” The harder question is whether any laboratory can build a procedure that actually instantiates that separation, confirms it, and reports its uncertainty. This paper draws a sharp line between two categories.

First are operational definitions: quantities realized by a physical procedure that can be repeated and audited. A path-length difference defined by an optical wavelength locked to an atomic reference is in this category. It can be measured interferometrically, recalibrated, and related back to a standard. This is what metrology normally means.

Second are conventions: quantities defined by fiat through a mapping that may be mathematically coherent but not physically testable at the claimed scale. Many statements about “Planck-scale distances between informational states” live here. The Planck length is a physically meaningful scale in theory, but that does not automatically make it a laboratory-accessible ruler for encoding or reading bits. If the calibration chain cannot be implemented, then “distance” is not a measured property; it is a chosen label. That distinction matters because it separates claims that can be falsified by measurement from claims that can only be debated as interpretive frameworks.

A practical symptom of this confusion is that “distance” gets used interchangeably for three different things: spatial separation of wavepackets, path-length differences in interferometers, and distance measures on quantum state space. These are not the same. A qubit can have two basis states with zero spatial separation (spin up/down in the same location) while being maximally distinguishable in Hilbert space. Conversely, two wavepackets can be spatially distinct and still highly overlapping as quantum states if their separation is tiny compared to their width. Without an explicit metrology, discussions collapse into verbal intuition, and the reader is left unable to tell whether a claim is about hardware geometry, mode structure, or abstract distinguishability.

The point of introducing metrology is therefore not to add bureaucracy. It is to prevent category errors. When someone says “these two qubit states are separated by X,” metrology forces the follow-up: separated in what sense, realized how, measured with what apparatus, traceable to what standard, and with what uncertainty? Once those questions are answered, many debates become less mystical and more technical, which is precisely the maturation pathway from speculative discourse to engineering reality.

1.3 Scope and contributions of the paper

This paper does not attempt to replace quantum information theory, nor does it attempt to solve quantum gravity. It is narrower and more practical: it proposes a disciplined vocabulary and two concrete standards for talking about “distance” in information-bearing systems, with explicit attention to what can be physically realized today.

The first contribution is a meter-realized metrology for a classical bit, defined as a calibrated path-length difference derived from an optical reference. This yields a reproducible “bit-distance” that can be instantiated in free-space optics, fiber, or integrated photonics and audited with standard interferometric techniques. The result is a bit definition whose unit is literally meters, not metaphor.

The second contribution is a state-space metrology for qubits that treats distance as experimentally accessible distinguishability, formalized as an angle on the Bloch sphere (or an equivalent overlap-based measure), and then mapped into meters using a calibrated phase-to-length conversion. This provides a bridge between the natural geometry of quantum states and SI-traceable measurement, while keeping clear what is being mapped and what is being physically separated.

The third contribution is a diagnostic framework for “scale claims,” especially those invoking Planck-scale language. The paper distinguishes declared scales from operational scales and gives criteria for when a claimed distance is a realizable metrological quantity versus a convention. The aim is not to dismiss ambitious ideas, but to keep the boundary between measurement and metaphor crisp enough that high-impact claims remain accountable.

Finally, the paper provides practical guidance: reference implementations, verification workflows, and reporting templates aimed at enabling cross-lab comparability. The broader objective is interoperability: not just that a device “works,” but that it can be compared, calibrated, and trusted across contexts. In that sense, the paper argues that information metrology is not a philosophical ornament; it is a necessary step in the transition from isolated demonstrations to reliable infrastructure.

2. Concepts and Definitions

Any attempt to build a metrology for bits and qubits succeeds or fails on one issue: whether the paper keeps “where things are” separate from “what state they are in.” In classical engineering, the distinction is often harmlessly blurred because the relevant degrees of freedom are macroscopic and robust. In quantum systems, the blur is fatal, because superposition and overlap make it possible for two states to occupy the same region of physical space while being maximally distinct in Hilbert space, or to be separated in space while still nearly identical as quantum states. This section fixes the vocabulary. The goal is not to burden the reader with formalism, but to ensure that when we say “distance,” we can state precisely what kind of distance we mean, what is being measured, and what calibration chain makes it an SI-traceable quantity.

2.1 Bit, qubit, and the difference between physical space and Hilbert space

A classical bit is an abstract two-valued variable, typically written as $\{0,1\}$. In physical hardware, a bit is realized by two stable, distinguishable macrostates of some system. The word “stable” matters: the bit is not merely a fleeting measurement outcome, but a configuration that persists long enough to be prepared, stored, transmitted, and read. In this paper, we use the term bit in the operational sense: a physical device implements a bit if it supports two distinguishable states, an initialization procedure, and a readout procedure with a quantifiable error probability.

A qubit is a two-dimensional quantum system. In abstract terms, it is a state vector in a complex two-dimensional Hilbert space, with measurement outcomes that can be associated with a chosen basis, often labeled $|0\rangle$ and $|1\rangle$. In physical terms, qubits can be realized in many ways: internal degrees of freedom (spin, polarization, hyperfine levels), collective excitations (superconducting circuits), or mode structure (path and time-bin photonics). The essential operational feature is not that the system is microscopic or exotic, but that it supports coherent superpositions and unitary evolutions that can be tested interferometrically or through controlled measurement statistics.

The critical distinction for this paper is between physical space and Hilbert space.

Physical space is where objects and fields are located, where distances are measured in meters, and where geometry is part of the operational language of the laboratory. If you say two components of an apparatus differ in length, that statement belongs to physical space.

Hilbert space is the abstract state space of quantum mechanics. Its “geometry” is not spatial; it is a geometry of probability amplitudes, inner products, and distinguishability. Two states can be orthogonal (perfectly distinguishable) even when they occupy the same region of physical space. Conversely, two states can be spatially separated and still have substantial overlap as quantum states, depending on their wavefunction width and other degrees of freedom.

Because metrology is the discipline of operational measurement, one cannot define “distance between qubit states” without saying whether one means a separation in physical space, a separation in mode structure, or a separation in Hilbert space. This paper’s central tactic is to separate these layers and then, when desired, build a traceable mapping from one to another rather than treating them as identical by intuition.

2.2 What “distance” can mean: spatial displacement, path length, phase, and distinguishability

The word “distance” will be used in this paper in several distinct senses, each legitimate but not interchangeable. The paper’s framework treats these as separate primitives.

Spatial displacement is literal separation in physical space. If an object can be localized near $x = 0$ or $x = d$, then d is a spatial displacement. In a “cat-like” spatial superposition qubit, one might imagine a state that is a coherent superposition of two localized wavepackets separated by d . Spatial displacement is measured directly in meters, but it is not automatically the right way to talk about qubits, since many qubits are not spatially encoded.

Path length is the optical or physical length of a propagation path in an apparatus. A path qubit is not defined by where a photon “is” in space in the everyday sense, but by which mode it occupies, often corresponding to distinct paths in an interferometer or distinct temporal modes. A path-length difference ΔL is a metrologically powerful object because it can be measured with interferometry and made traceable to frequency standards. In this paper, meter-realized bit metrology is primarily based on controlled path-length differences.

Phase is a derived but central quantity. A path-length difference produces a phase shift at a given wavelength. The essential point is that phase is often easier to measure with high precision than absolute distance, because phase can be measured interferometrically as a relative quantity. In interferometric systems, the conversion between path-length difference and phase is controlled by the wavelength of the probe. Because wavelength can be derived from frequency standards, phase becomes an “information handle” that can be tied back to SI units through a calibration chain.

Distinguishability is the operational notion of “how far apart” two states are in the sense of measurement. For classical bits, distinguishability is threshold separability: how reliably can one decide whether the system is in state 0 or state 1 under noise? For qubits, distinguishability is more subtle because quantum states can be non-orthogonal. Two non-orthogonal quantum states cannot be perfectly distinguished in a single shot by any measurement, which means “distance” in the operational sense is naturally tied to overlaps and statistical decision theory. This is one reason a state-space metrology for qubits is attractive: it aligns directly with what can be measured and verified experimentally.

These notions relate but do not collapse into one another. Spatial displacement can change overlap, but not in a simple “more meters equals more orthogonality” way unless wavepackets are sufficiently narrow and other degrees of freedom are controlled. Path-length differences produce phase shifts, but phase shifts depend on wavelength and dispersion. Distinguishability can be increased by orthogonality of modes even when spatial separation is zero, as with polarization qubits. Because of this, the paper treats “distance” as a term that must always be annotated by its type: distance in space, distance in path length, distance in phase, or distance in state space.

A useful conceptual slogan for the rest of the paper is: for qubits, “distance” is most naturally defined first as distinguishability, then mapped into meters through a calibrated interferometric relationship if meters are desired.

2.3 Requirements for physical metrology: reproducibility, traceability, and uncertainty budgets

Physical metrology is not merely a definition; it is a discipline of realization. The question is not “can we define a quantity,” but “can independent laboratories realize it and agree within a known uncertainty.” This paper uses three requirements as the boundary between operational metrology and convention.

Reproducibility means that a procedure can be performed by different groups and yield comparable results. For a bit or qubit standard, reproducibility requires that state preparation be specified (how do we set the system to 0 or 1, or prepare a specified qubit state), and that readout be specified (how do we decide what state it is in). Reproducibility also implies environmental constraints: temperature, vibration, electromagnetic interference, and drift must be accounted for in the standard’s operating conditions.

Traceability means that the quantity can be related to recognized standards through a calibration chain. In SI-based metrology, traceability is not a philosophical label; it is a concrete chain of comparisons. In the framework of this paper, traceability for “distance in meters” is achieved by tying length measurements to optical frequency standards, so that wavelength becomes a derived standard and interferometry becomes a measurement engine. For qubits, traceability is more nuanced: state-space distance is not an SI quantity by itself, but it can be related to calibrated phase shifts and thus to length standards if the mapping is explicitly specified and verified.

Uncertainty budgets are the heart of metrology. Any claimed distance must come with an account of the dominant error sources and their contributions. For meter-realized path-length standards, uncertainties include thermal expansion, refractive index fluctuations, dispersion, polarization mode coupling, mechanical vibrations, laser frequency drift, and detector noise. For

qubit distance standards, uncertainties include state preparation errors, measurement calibration errors, phase noise, mode mismatch, decoherence, and statistical sampling error. The point is not to list every possible imperfection, but to provide a structured accounting that makes the claimed distance meaningful as a reported measurement rather than a nominal parameter.

These requirements also illuminate why some appealing declarations are not metrology. For example, one can declare that the separation between 0 and 1 is the Planck length, or that the separation between superposed qubit components is the Planck length, but unless there is a realizable procedure that can instantiate and verify that length difference with traceability and uncertainty accounting, the statement is a convention rather than a measurement. In metrology terms, it is not wrong; it is simply not a laboratory standard. The paper's purpose is to keep this boundary crisp and to provide standards that live on the operational side of it.

By establishing these concepts and requirements, the remainder of the paper can proceed without ambiguity. When we define a bit-distance or a qubit-distance, we will specify which type of distance is intended, how it is realized physically, how it is measured, what it is traceable to, and how its uncertainty should be reported. This allows the paper to move from philosophical language to implementable standards without smuggling in hidden assumptions about what "distance" must mean.

3. Meter-Realized Bit Metrology via Path-Length Encoding

The simplest way to make a bit metrological is to define it by a length difference that can be realized, measured, and re-measured using standard interferometry. The intent is not to claim that all bits "are" lengths, but to provide at least one reference implementation in which a bit's defining separation is explicitly a meter-scale quantity with SI traceability. Path-length encoding is attractive for three reasons. First, it directly leverages the most mature precision-measurement technology in physics: interferometry. Second, it naturally connects to frequency standards, making traceability straightforward. Third, it makes the meaning of "distance between 0 and 1" literal, auditable, and platform-independent: different labs can build different hardware and still agree on the realized bit-distance if they share the same wavelength standard and verification procedure.

3.1 Device concept: two paths, one calibrated length difference

At the device level, the bit is implemented as a controlled choice between two propagation paths, Path A and Path B, in which the optical path length differs by a calibrated amount ΔL . The physical carrier can be light (preferred for precision), but the core idea is broader: there are two distinguishable macrostates whose difference is a known geometric quantity in meters.

A reference architecture is an interferometric switch with three conceptual modules:

First, a source module that launches a stable coherent field into the device. Coherence matters because interference is the readout mechanism.

Second, a path module that provides two well-defined routes. The “0” state corresponds to choosing Path A, and the “1” state corresponds to choosing Path B. The key design requirement is that the optical path length difference ΔL be stable on the timescale of measurement and calibratable against a reference.

Third, a recombination and detection module that brings the two paths into interference. This provides a high-contrast measurement of the path difference and thus a high-confidence decision rule for identifying whether the system is in the 0-path or 1-path state.

The design can be realized as a Mach–Zehnder interferometer, a Michelson interferometer, or a fiber loop with a controlled delay. The essential point is not the specific topology but the existence of two paths whose relative length is the defining metrological object.

One subtlety is that “length” in optical systems is usually optical path length rather than geometric length. Optical path length includes refractive index. That is not a defect; it is an advantage, because optical path length is exactly what interferometers measure. The metrological standard therefore naturally lives in optical path length, with explicit accounting for refractive index variations where relevant.

3.2 Defining the bit-distance: $d_{\text{bit}} = \lambda_0 / 2$

To make the bit-distance SI-traceable, we anchor it to a reference wavelength λ_0 derived from a reference frequency f_0 by

$$\lambda_0 = c / f_0$$

where c is the speed of light in vacuum and f_0 is provided by a stabilized optical source referenced ultimately to an atomic clock or a recognized frequency standard.

We then define the canonical bit-distance as

$$d_{\text{bit}} = \lambda_0 / 2.$$

This choice is not arbitrary. A path-length difference of $\lambda_0 / 2$ corresponds to a phase shift of π at wavelength λ_0 , which yields maximal contrast in interference. In a practical sense, it is the smallest nontrivial path-length difference that flips the interference output from constructive to destructive (or vice versa) at the reference wavelength. That makes it an ideal “unit step” for a bit encoded in path length: it is both small enough to be easily realized and large enough to produce a strong interferometric signature.

Because λ_0 is derived from a frequency standard, d_{bit} becomes a length standard. Two laboratories that share the same reference frequency can realize the same d_{bit} even if their mechanical implementations differ. This is precisely the metrological goal: remove dependence on idiosyncratic hardware geometry and tie the quantity to a reproducible reference.

In media with refractive index n , the same idea can be expressed in terms of optical path length. If the physical path difference is L_{phys} and the relevant effective index is n_{eff} , then the optical path difference is

$$\Delta L_{\text{opt}} = n_{\text{eff}} * L_{\text{phys}}.$$

The canonical condition for the bit-distance becomes $\Delta L_{\text{opt}} = \lambda_0 / 2$, with n_{eff} included explicitly in the calibration and uncertainty budget. This is important in fiber and integrated photonics, where refractive index, dispersion, and mode structure are central.

3.3 Readout by interference: maximizing distinguishability

A metrological bit is only useful if it is read out with a defined decision rule and a quantifiable error probability. Interference provides a natural readout because it converts path-length difference into a measurable intensity difference.

In an ideal two-path interferometer, the output intensity depends on the relative phase

$$\phi = (2 \pi / \lambda_0) * \Delta L_{\text{opt}}.$$

When ΔL_{opt} equals $\lambda_0 / 2$, ϕ equals π , producing a maximal swap between constructive and destructive interference in a chosen output port. This yields the largest possible separation of output distributions for the two bit states in the presence of additive noise, which is exactly what “maximizing distinguishability” means operationally.

From a decision-theory perspective, interference readout reduces the bit decision to a thresholding problem: measure the output intensity (or differential intensity between two ports), compare it to a threshold, and decide “0” or “1.” The corresponding bit error rate can be estimated empirically by repeated preparations of each state under controlled conditions. This allows the standard to be reported not just as “a length difference,” but as a length difference plus an associated operational distinguishability under specified noise and drift conditions.

Interferometric readout also provides an intrinsic self-check: visibility. The interference fringe visibility is a single number that encodes mode overlap, coherence, and stability. High visibility indicates that the apparatus is well-aligned and that the bit states are being realized consistently. Low visibility indicates that the bit-distance is not being instantiated in a stable way, or that uncontrolled degrees of freedom are leaking which-path information. In this

paper's framework, visibility becomes a key diagnostic parameter and a required reported quantity in any metrological implementation.

3.4 Practical implementation options: free-space, fiber, integrated photonics

The same metrological concept can be realized in multiple hardware platforms. Each has distinct advantages and dominant uncertainty sources.

Free-space optics offers intuitive geometry and easy access to alignment. High-quality mirrors and beamsplitters can yield very high interference visibility. Free-space implementations are ideal for laboratory reference devices and for demonstrating the traceability chain clearly. However, free-space systems are sensitive to vibration, air turbulence, and thermal gradients, making enclosure and environmental control important.

Fiber-based implementations offer compactness, long interaction lengths, and mechanical stability once packaged. A fiber interferometer with a controlled delay line can realize $\Delta L_{\text{opt}} = \lambda_0 / 2$ with excellent repeatability. Fiber systems are attractive for real-world deployment, but they introduce sensitivity to polarization drift, temperature-dependent refractive index changes, and dispersion. Polarization-maintaining fiber, careful splicing, and active stabilization are often required to achieve metrological-grade performance.

Integrated photonics offers the promise of manufacturability and portability. On-chip interferometers can realize path-length differences lithographically and can be combined with phase shifters for tuning and calibration. Integrated devices can be packaged to reduce environmental sensitivity, and arrays of devices can be produced for inter-lab comparisons. However, integrated systems require careful modeling of effective index, temperature sensitivity, and fabrication tolerances. For metrology, the key is not merely that the device can be fabricated, but that the realized ΔL_{opt} can be calibrated and verified against the frequency-derived wavelength standard.

The important unifying point is that “bit-distance” is not defined by the physical layout alone. It is defined by the measured and calibrated optical path difference as referenced to λ_0 . This makes the standard portable across platforms while preserving SI traceability.

3.5 Error sources: thermal drift, dispersion, polarization, mechanical noise

A length-defined bit is only as good as its stability. The main error sources are those that change ΔL_{opt} or reduce interference visibility, thereby increasing the bit error rate and expanding the uncertainty budget.

Thermal drift affects both physical length and refractive index. Materials expand with temperature, and refractive index changes with temperature as well. In fiber and integrated photonics, refractive index drift can dominate. Even if the physical length is stable, the optical

path length may wander. Thermal stabilization, insulating enclosures, and active feedback are standard mitigation strategies. In metrological reporting, temperature coefficients should be measured and included in the uncertainty budget.

Dispersion matters because interferometric phase depends on wavelength, and real sources have finite linewidth. In addition, in broadband or multiwavelength systems, different spectral components accumulate different phases, reducing visibility. Even with a narrowband source, dispersion can couple with environmental changes to produce phase drift. For a frequency-locked narrow linewidth laser, dispersion is often manageable, but it becomes important in fiber and integrated platforms when temperature or stress changes the effective index profile.

Polarization effects are a major source of fringe degradation. If the two paths rotate polarization differently, the recombined fields will not fully interfere, reducing visibility and making the readout less distinguishable. Polarization mode dispersion and birefringence fluctuations in fiber are especially relevant. Polarization-maintaining components, polarization controllers, and polarization diversity detection can mitigate these effects, but the mitigation must be explicitly part of the standard operating procedure.

Mechanical noise and vibration cause real-time changes in path length. In free-space systems, acoustic noise and vibrations can couple strongly. In fiber systems, bending and stress change effective index and physical length. In integrated systems, packaging strain and microphonics can couple into phase. The metrological response is to specify the measurement bandwidth and to control or measure the vibration environment. Practically, this means defining an averaging time, specifying allowable vibration levels, and reporting phase noise spectra when relevant.

Finally, it is essential to separate two kinds of failure: drift of the mean ΔL_{opt} and loss of visibility. Drift can sometimes be actively stabilized with feedback, maintaining a target $\Delta L_{\text{opt}} = \lambda_0 / 2$. Loss of visibility indicates a deeper loss of mode overlap or coherence and cannot always be corrected by simple feedback. In a metrological framework, both must be tracked. The standard must specify not only the nominal bit-distance, but also the minimum acceptable visibility and the maximum allowable drift over defined time intervals.

Taken together, these elements define a meter-realized bit metrology that is implementable today: a bit whose defining separation is a calibrated optical path-length difference tied to a frequency standard, read out by interference, and reported with explicit uncertainty sources. This provides the foundation on which the next sections build: extending the same discipline to qubits, where distinguishability must be handled more carefully and where “distance” in state space becomes the natural primitive.

4. Traceability Chain: Atomic Clock to Laser Frequency to Length

A metrology for a bit that claims “distance in meters” must answer a simple question: how does a number that appears at the output of an interferometer become traceable to a recognized standard? The answer is a calibration chain. The chain begins with time (frequency), because modern measurement science has learned to make frequency the most stable and transferable quantity, and then it converts frequency into wavelength, and wavelength into length through interference. This section formalizes that chain in a way that is practical across laboratories, while also making explicit where assumptions enter (for example, whether the relevant propagation is in vacuum or a medium with refractive index).

4.1 Frequency locking and optical references

The traceability chain starts by establishing a stable optical frequency f_0 for the probe field used in the interferometer. Stability here has two layers: short-term stability (linewidth and phase noise) and long-term accuracy (agreement with a recognized reference). Both matter, but in different ways.

A frequency reference can be obtained in two broad ways.

One approach is atomic or molecular spectroscopy. A laser can be locked to a narrow transition whose frequency is repeatable across laboratories. This yields an optical frequency reference that is ultimately tied to the same physics everywhere: the energy difference between two quantized levels. The implementation details may vary, but the operational point is that the reference is not a human artifact; it is a property of nature that can be re-realized.

A second approach is an optical cavity. A laser can be locked to a high-finesse cavity mode. This gives exceptional short-term stability and low phase noise, which is valuable for interferometry. However, cavities drift over long times due to temperature, aging, and mechanical creep. For metrology, cavity locking is often paired with an atomic reference or periodically calibrated against one. In other words, the cavity provides stability; an atomic reference provides accuracy and reproducibility.

The most powerful modern bridge between “clock” and “laser” is the optical frequency comb. A comb acts like a gear train connecting a stable clock-derived repetition rate to optical frequencies. In practical terms, it allows an atomic clock (or another primary time standard) to discipline the optical frequency f_0 , either directly or through intermediate references. The conceptual contribution for this paper is that the comb makes the traceability chain explicit: it is the device that lets one say, with operational clarity, that the laser frequency used to define the bit-distance is tied to the clock.

For this paper’s purposes, the details of which lock is used are less important than the metrological structure:

- A stable timebase exists (clock).
- A laser is frequency-locked to a reference.
- The lock is verified by measurable diagnostics (beat notes, error signals, drift logs).
- The residual instability and bias are quantified and carried into the uncertainty budget.

This is what makes the later statement “ λ_0 is known” meaningful rather than rhetorical.

4.2 Converting frequency to wavelength and wavelength to length

Once the probe laser has a known frequency f_0 , the vacuum wavelength λ_0 is defined by

$$\lambda_0 = c / f_0$$

where c is the speed of light in vacuum. This step is conceptually simple, but physically it hides an important choice: are we measuring length in vacuum or in a medium?

Interferometers measure optical phase accumulated along a path. In vacuum, a path-length difference ΔL directly corresponds to a phase difference

$$\phi = 2\pi\Delta L / \lambda_0.$$

In a medium, the phase depends on the optical path length, not the geometric length. If the effective refractive index is n_{eff} , then a geometric path difference ΔL_{geom} corresponds to optical path difference

$$\Delta L_{\text{opt}} = n_{\text{eff}} * \Delta L_{\text{geom}}$$

and the phase becomes

$$\phi = 2\pi\Delta L_{\text{opt}} / \lambda_0.$$

For a “length-defined bit,” this is not a complication but a specification: the metrological object is ΔL_{opt} unless the apparatus is explicitly in vacuum. If the platform is fiber or integrated photonics, then n_{eff} is not merely a constant; it depends on temperature, strain, wavelength, and polarization. Therefore, the conversion from frequency to wavelength to length is exact in principle but operationally limited by how well the relevant n_{eff} is controlled or characterized.

The step “wavelength to length” is implemented by interference. The interferometer does not need to measure absolute length; it measures phase, and phase encodes length relative to a wavelength standard. This is why the choice $d_{\text{bit}} = \lambda_0/2$ is so convenient: it corresponds

to a phase shift of π , which is maximally robust to readout noise in a properly balanced interferometer.

In summary, the chain is:

- define f_0 by frequency locking
- compute λ_0 from c/f_0
- realize length differences as phase differences measured interferometrically
- interpret those phase differences as ΔL (vacuum) or ΔL_{opt} (medium), explicitly stated

This framework is compatible with free-space, fiber, and integrated platforms, provided the medium parameters are either controlled or included in the uncertainty budget.

4.3 Calibration workflows and verification tests

A metrology is only real if a lab can follow a workflow and know when they have succeeded. The calibration workflow for a length-defined bit should be simple enough to be repeatable and strict enough to be auditable. A practical workflow has four phases: establish the optical reference, set the nominal bit-distance, verify by interference, and monitor drift.

First, establish the optical reference. The laser is locked to the chosen reference (atomic transition, cavity, or comb-disciplined clock) and the lock quality is assessed. This step produces the declared f_0 and a record of its stability over the measurement interval.

Second, set the nominal bit-distance. The apparatus is adjusted so that the optical path difference between the two bit states satisfies

$$\Delta L_{\text{opt}} = \lambda_0/2.$$

In practice this can be done by scanning a phase actuator and locating the condition where the interference output flips between constructive and destructive, or where two output ports exchange power symmetrically. The aim is not merely to “hit the point,” but to record the actuator setting (or physical configuration) that corresponds to the π phase shift.

Third, verify by interference. Verification is done by measuring fringe visibility and repeatability. Visibility is the simplest single-number diagnostic of whether the two paths are interfering cleanly. Repeatability is checked by re-preparing the 0 and 1 states many times and measuring the distribution of the readout variable. A metrological bit is not defined by a single successful fringe; it is defined by a stable separation that yields a stable decision boundary.

Fourth, monitor drift. Any realized ΔL_{opt} will drift due to temperature, vibration, and index fluctuations. Drift monitoring can be passive (record the readout over time) or active (servo the phase actuator to maintain the π condition). In metrology, either is acceptable, but the choice must be declared because it changes the meaning of the reported uncertainty. Passive monitoring characterizes the device as it is. Active stabilization characterizes the combination of device and control loop, which is often the practical object of interest.

Verification tests should include at least the following categories:

- Lock verification tests that confirm f_0 stability over the measurement window.
- Interferometric fringe tests that confirm visibility above a declared threshold.
- Repeatability tests that estimate bit error probability under stated conditions.
- Environmental sensitivity tests that measure coefficients such as $d(\phi)/dT$, $d(\phi)/d(\text{strain})$, and polarization sensitivity if relevant.

These tests do not require exotic equipment beyond what precision optics laboratories already use, but they impose discipline: the “bit-distance” is not a nominal design value; it is a measured and verified quantity.

4.4 Uncertainty budget structure for a length-defined bit

A credible metrology must publish an uncertainty budget, even if the first implementation is coarse. The key is not to pretend to perfection, but to structure uncertainty in a way that other laboratories can reproduce and improve.

For a length-defined bit, uncertainties naturally split into four layers.

Frequency uncertainty. This includes the accuracy and stability of f_0 and any transfer uncertainty if a comb or intermediate reference is used. Frequency uncertainty propagates into wavelength uncertainty and therefore into the inferred length. In many practical cases, frequency uncertainty will be far smaller than other contributions, but it must still be stated to preserve traceability.

Phase measurement uncertainty. The interferometer measures phase through intensity. Noise in detectors, finite contrast, digitization noise, and finite averaging time all contribute. If the readout is a thresholded bit decision, this uncertainty shows up as a bit error probability and as a confidence interval on that probability.

Optical path uncertainty. This is often the dominant layer in non-vacuum platforms. It includes thermal expansion of path components, thermo-optic changes in refractive index, stress-induced index changes, and dispersion-related effects if the source is not perfectly

monochromatic. In fiber and integrated photonics, polarization mode coupling can appear here as well, because it reduces effective interference and can bias the inferred phase.

Model uncertainty and environmental coupling. Any conversion from measured phase to inferred length depends on a model: vacuum versus medium, the value of n_{eff} , and assumptions about mode purity. Environmental coupling terms quantify how sensitive the system is to temperature, vibration, acoustic noise, and electromagnetic interference. Even if these are mitigated, residual couplings remain and must be bounded.

A practical reporting structure is:

- report the realized d_{bit} as a nominal value ($\lambda_0/2$ expressed in meters)
- report the measured phase stability around π over a stated time window
- report fringe visibility and its drift
- report an uncertainty budget with dominant terms and how they were estimated

This structure makes two things clear. First, the standard is genuinely metrological because it is tied to a traceable f_0 . Second, the standard is operationally meaningful because it includes the device physics that determines whether “ $\lambda_0/2$ ” is actually realized in the laboratory rather than merely declared on paper.

With this traceability chain and uncertainty structure in place, the “meter-realized bit” becomes a reproducible artifact: a bit whose defining separation is not a metaphor, but a length measurement disciplined by the most stable measurement resource modern science possesses, namely frequency.

5. Meter-Realized Qubit Metrology via Mode Separation

A qubit invites an immediate temptation: to treat its two basis states as “two places” and to demand a literal distance between them. That temptation is usually misplaced, because most qubits are not spatial alternatives; they are orthogonal modes of a single system. The metrologically correct move is to locate the qubit in a physical degree of freedom that can be realized and measured with high precision. For photonic platforms, and for any architecture that can exploit interferometry, the cleanest option is mode separation: the logical basis states correspond to two orthogonal propagation modes that can be engineered as two paths or two time bins. In such systems, the qubit is not defined by where a particle “is” in everyday space, but by which mode it occupies, and “distance” in meters enters as an optical path-length difference or a calibrated delay. This section extends the bit metrology of Section 3 to qubits, while keeping the quantum distinctions intact: a qubit can be coherent across the two modes, it

can carry relative phase, and its “distance” must be defined in a way that respects superposition rather than treating the basis states as merely classical alternatives.

5.1 Path qubits and time-bin qubits as metrological primitives

A mode-encoded qubit is a two-mode quantum system in which the computational basis corresponds to mutually orthogonal modes. Two of the most important examples are path qubits and time-bin qubits, because both can be implemented with the same interferometric toolkit that makes length metrology powerful.

A path qubit uses two spatially distinct propagation modes in an interferometer. The basis states can be labeled as $|A\rangle$ and $|B\rangle$, corresponding to the photon occupying Path A or Path B. Crucially, these are modes of the same field, and they can be engineered to be orthogonal by design: they propagate in different waveguides or different arms of an interferometer. Orthogonality here is physical: it is enforced by distinct boundary conditions and mode structure, not by an assumption that the photon is a classical object at a point.

A time-bin qubit uses two temporal modes traveling along the same physical path. The basis states are $|early\rangle$ and $|late\rangle$, corresponding to a pulse arriving in one of two time windows separated by a delay ΔT . The two bins are orthogonal if their temporal waveforms do not overlap appreciably in the detection basis. The advantage is immediate: the “two states” can occupy the same fiber and the same spatial path, which reduces sensitivity to polarization mismatch and many spatial alignment issues. Time-bin encoding is therefore widely used in quantum communications where environmental stability is challenging.

From a metrology perspective, path and time-bin qubits are primitives because they attach the qubit’s definition to a measurable classical parameter: a path-length difference ΔL (path qubit) or an equivalent delay ΔT (time-bin qubit). These parameters are precisely the quantities that modern measurement science can control and calibrate. The qubit’s coherence then becomes testable through interference, rather than assumed.

5.2 Defining a canonical qubit separation as a calibrated path-length difference

To make a “meter-realized qubit metrology,” we need to define what “separation” means in a way that is both physically implementable and consistent with quantum mechanics. For mode-encoded qubits, the natural candidate is not a spatial displacement of a particle but the optical path-length difference that separates the two modes or temporal bins.

In a path qubit, define the canonical separation as the optical path-length difference between the two arms:

$d_{\text{qubit}} := \Delta L_{\text{opt}}$.

In a time-bin qubit, define the canonical separation as the equivalent distance light travels in the time delay:

$d_{\text{qubit}} := c * \Delta T$ (in vacuum), or more generally $d_{\text{qubit}} := (c/n_{\text{eff}}) * \Delta T$ if the propagation medium is specified.

The simplest way to choose a canonical qubit separation is to tie it to the same wavelength standard used for bit metrology. For a reference wavelength λ_0 , one can select a canonical path difference such as:

$\Delta L_{\text{opt}} = \lambda_0 / 2$ (a π phase shift at λ_0), or $\Delta L_{\text{opt}} = m * \lambda_0$ for integer m , depending on design constraints.

However, it is important to clarify what this “separation” does and does not mean. It does not mean that the two basis states are separated by that distance in ordinary space as two localized objects. It means the two orthogonal modes are defined by a device whose physical parameter ΔL_{opt} can be measured in meters and calibrated traceably. The qubit’s physical instantiation therefore has a metrological “dial” that is length-like, even though the qubit’s fundamental geometry remains a Hilbert-space object.

In this sense, the qubit separation is a property of the apparatus that defines the mode structure, not a property of a particle’s location. The metrological virtue is that ΔL_{opt} can be reported, compared across labs, and used to reproduce the same class of qubit implementations with an explicit uncertainty budget.

5.3 Interference and phase control as the operational handle

Mode-encoded qubits are testable because they can interfere. Interference is not merely a readout trick; it is the operational criterion that the qubit exists as a coherent two-mode system rather than a classical random switch between alternatives.

A generic mode qubit can be written as:

$$|\psi\rangle = a |0_{\text{mode}}\rangle + b e^{i\phi} |1_{\text{mode}}\rangle,$$

where ϕ is the relative phase between the modes. In a path qubit, ϕ is directly controlled by the optical path difference and phase shifters. In a time-bin qubit, ϕ is controlled by the phase accumulated across the delay and by interferometric recombination. The key point is that ϕ is experimentally accessible: it can be tuned and measured.

Phase control provides the operational handle for qubit metrology because it connects three measurable domains:

- path-length difference in meters

- phase shift in radians
- qubit rotation angle on the Bloch sphere for mode-encoded qubits

In practice, the qubit is characterized by preparing known states (for example, equal superpositions with controlled relative phase) and verifying them by interference fringes and measurement statistics. If changing a calibrated phase actuator produces the expected sinusoidal variation in detector counts with high visibility, then the apparatus is realizing coherent superpositions. If the response is washed out, the system has either lost coherence or the modes are not properly matched.

For metrology, this suggests a simple principle: the qubit separation is not “verified” by measuring a mechanical length with calipers; it is verified by demonstrating the expected phase dependence under controlled tuning, with measured visibility and stability. This is the quantum analog of “calibration by functional behavior”: the device is calibrated not only geometrically but operationally, by the coherence behavior it enables.

5.4 Maintaining orthogonality: when “overlap” kills the qubit

A mode-encoded qubit requires that the two basis modes be orthogonal to a good approximation. Orthogonality is the hidden non-negotiable: if the modes are not orthogonal, then the system is not well described as a two-dimensional logical space, and all downstream claims about fidelity, error rates, and distance become ill-defined.

In a path qubit, orthogonality is typically strong because distinct arms define distinct spatial modes. But orthogonality can be degraded by mode mixing, back-reflections, imperfect couplers, or cross-talk in integrated waveguides. In a time-bin qubit, orthogonality depends on temporal separation relative to pulse width and detector resolution. If the early and late wavepackets overlap in time or cannot be resolved by the measurement apparatus, then the basis states are not reliably distinguishable.

This is where “overlap kills the qubit” becomes more than a slogan. Overlap has two related meanings:

First, overlap as state overlap. If the physical states corresponding to $|0_{\text{mode}}\rangle$ and $|1_{\text{mode}}\rangle$ are not orthogonal, then no measurement can reliably distinguish them in the intended basis. This reduces the effective dimensionality of the logical space and imposes a ceiling on achievable performance.

Second, overlap as mode mismatch. Even if the modes are conceptually distinct, practical imperfections can cause partial distinguishability through additional degrees of freedom: polarization drift, spectral differences, spatial mode mismatch, or timing jitter. These mismatches introduce which-mode information to the environment or to the detector, reducing

interference visibility. Reduced visibility is not merely an aesthetic defect; it is the observable signature that the device is failing to realize a coherent qubit.

A metrological standard must therefore include orthogonality maintenance as a requirement, not as a best practice. This can be stated operationally: the implementation is accepted as a qubit realization only if it demonstrates interference visibility above a declared threshold under specified conditions, and only if the mode separation parameter (ΔL_{opt} or ΔT) is large enough to keep the basis resolvable but not so large as to introduce uncontrolled dispersion and drift. In other words, qubit metrology requires a balance between separability and stability.

5.5 Decoherence channels specific to mode-encoded qubits

Mode-encoded qubits have distinctive decoherence mechanisms that differ from, for example, spin qubits or superconducting qubits. Because the qubit lives in modes that propagate through an apparatus, decoherence often enters through path-dependent phase noise and mode-dependent loss rather than through local coupling to a thermal bath.

Phase noise is the primary channel. Any fluctuation in optical path length, refractive index, or timing delay induces fluctuations in the relative phase ϕ . In a path qubit, vibrations, thermal drift, and acoustic noise perturb ΔL_{opt} . In a time-bin qubit, timing jitter, dispersion-induced pulse distortion, and fluctuations in propagation velocity perturb ΔT . Phase noise dephases the superposition, reducing coherence and flattening interference fringes.

Mode-dependent loss is another key channel. If one mode suffers higher loss than the other, then the qubit undergoes amplitude damping in the mode basis. In addition to reducing count rates, mode-dependent loss biases measurement statistics and can distort the effective qubit state, especially in long links or in integrated devices with asymmetric couplers. Importantly, loss is not always “just loss” in quantum systems; when loss is correlated with mode, it becomes information leakage.

Dispersion and spectral effects matter because mode-encoded qubits depend on waveform integrity. In time-bin qubits, dispersion can broaden pulses, causing overlap between bins and reducing basis distinguishability. In path qubits, dispersion can cause wavelength-dependent phase shifts and reduce interference visibility if the source has finite linewidth or if the system operates over a spectrum.

Polarization coupling is often a silent decoherence channel. Even if the qubit is encoded in path or time, polarization can act as an uncontrolled tag. If the two modes experience different polarization transformations, then polarization carries which-mode information and reduces coherence. This is why polarization management is frequently essential even when polarization is not the qubit degree of freedom.

Finally, environmental entanglement is the unifying picture: decoherence occurs when information about the mode becomes available to degrees of freedom outside the intended two-mode system. In mode qubits, that “outside world” can be the uncontrolled polarization state, scattering into unguided modes, spectral distinguishability, or even thermal fluctuations that imprint path-dependent phase. The metrological implication is that a qubit standard cannot simply specify ΔL_{opt} ; it must also specify the conditions under which coherence is maintained and how decoherence is diagnosed and bounded.

In summary, a meter-realized qubit metrology via mode separation is feasible because it leverages mature interferometric calibration tools. But it requires a disciplined distinction: the metrological “distance” is a calibrated apparatus parameter (path-length difference or delay), while the qubit’s real operational integrity is verified through interference visibility, phase control, and explicit control of overlap and decoherence channels. This sets the stage for the next move in the paper: defining qubit distance in state space as distinguishability, and only then mapping that distance into meters in a controlled and declared way.

6. State-Space Metrology for Qubits: Distance as Distinguishability

A meter-realized approach is valuable because it makes “distance” literal, but it is not the natural language of qubits. A qubit is not fundamentally a pair of places; it is a point in a two-dimensional complex state space. The correct primitive notion of “how far apart two qubit states are” is therefore not a spatial separation but an operational one: how distinguishable are the states by any allowed measurement? This section makes that idea precise and treats it as the basis of a qubit metrology. The central move is to define distance in state space using quantities that are experimentally accessible and platform-independent, and only then, if desired, map those distances into meters using an explicitly declared conversion that rides on interferometric phase calibration. In other words, we do not begin by forcing qubits into meters; we begin by measuring what qubits actually are and only then translate into SI language if there is a reason to do so.

6.1 Bloch sphere geometry and the operational meaning of angles

For a single qubit, the set of pure states can be represented as points on the Bloch sphere. This representation is not merely pedagogical; it encodes an operational fact: any pure qubit state can be reached from any other by a unitary rotation, and those rotations can be parametrized by angles. The Bloch sphere turns the qubit’s state space into a geometry, in which “separation” corresponds to angular distance.

The operational meaning of a Bloch-sphere angle is tied to measurement statistics. Two states that are far apart on the sphere yield very different measurement outcomes in suitable bases.

Two states that are close yield similar outcome statistics no matter what measurement is chosen. In the extreme case, orthogonal states sit at opposite points of the sphere and can be perfectly distinguished in a single-shot measurement if measured in the right basis. Identical states correspond to the same point and cannot be distinguished at all. Everything else lies between: a continuous spectrum of partial distinguishability.

This connection between geometry and distinguishability is the reason angles on the Bloch sphere are metrologically meaningful. They correspond to measurable differences in probability distributions, not to a metaphor. A qubit metrology that is faithful to physics should therefore treat the qubit's natural geometry as the primary object and regard "distance" as a statement about measurable statistical separation.

One can summarize the key property as follows: in qubit state space, "angle" is a physically meaningful quantity because it controls the best achievable discrimination performance between two states. That is precisely what a metrology needs: a quantity defined by what can be operationally verified.

6.2 Inner products and experimental observables

The geometry of pure quantum states is encoded in inner products. For two pure qubit states $|\psi\rangle$ and $|\phi\rangle$, the magnitude of the inner product $|\langle\psi|\phi\rangle|$ measures how much the states overlap. This overlap is not an abstract number; it is directly connected to interference and to discrimination limits.

Two points are worth making explicit.

First, overlap controls interference. In an interferometric experiment where two alternative state preparations are recombined, the visibility of the interference pattern depends on coherence and on the degree to which the two alternatives are truly the same mode with different relative phase versus genuinely distinguishable states. In many platforms, especially photonics, overlaps show up as fringe contrast and as stable phase relations that can be experimentally mapped.

Second, overlap controls distinguishability. If two states have large overlap, no measurement can reliably tell them apart in a single shot. If they are orthogonal (overlap zero), there exists a measurement that distinguishes them perfectly. This is an operational boundary, not a matter of interpretation.

The practical challenge is that inner products are not measured directly as "dot products." They are inferred from measurement statistics. That inference can be done in more than one way: state tomography, direct overlap estimation protocols, or interference-based measurements depending on platform. The guiding principle is that any metrological definition must specify

which experimental observables are used to infer the overlap and what calibration steps are required to ensure the inference is accurate.

For mixed states, the story generalizes: one can no longer describe the state as a point on the sphere surface, but rather as a point inside the Bloch ball. Distinguishability then depends not only on relative orientation but also on purity. This complicates geometry but also makes metrology more realistic, because real devices produce mixed states due to noise and decoherence. In a metrological framework, the distance between states should be defined in a way that still makes sense when the states are not pure.

6.3 Distance measures and why they are metrologically attractive

The purpose of a distance measure in metrology is not to impress with mathematical elegance; it is to provide a reproducible way to compare states and to quantify uncertainty. Several distance measures are commonly used in quantum information because they align well with operational tasks such as discrimination, fidelity estimation, and error analysis.

A key metrological desideratum is monotonicity with distinguishability: if one pair of states is easier to tell apart than another pair, the distance should be larger. Another desideratum is robustness: the distance should not be hypersensitive to tiny experimental noise, and it should degrade gracefully when states become mixed.

Three families of measures are especially relevant.

First, angle-based measures for pure states. For pure states, the geometric angle between them captures their overlap. This is attractive because angles are bounded, interpretable, and naturally connected to rotations (which are what experimental controls often implement). It also makes reporting intuitive: “these two prepared states are separated by θ with uncertainty δ_θ .”

Second, fidelity-based measures. Fidelity measures how close two states are, and can be defined for mixed states as well as pure. Fidelity is attractive for metrology because it is directly related to performance claims: if a device claims to prepare a target state, fidelity tells you how close the prepared state is to that target, and its estimation can be structured with statistical confidence intervals.

Third, discrimination-based measures. These distances are tied explicitly to the best achievable error probability for distinguishing states. Such measures are metrologically attractive because they connect directly to operational capability. If two states are “close,” you can quantify that closeness as a lower bound on how many samples are required to tell them apart with a specified confidence.

In this paper’s framing, the most important point is not which measure is philosophically “best,” but that the chosen measure must be explicitly specified and must be linked to an experimental estimation protocol. A distance measure becomes a metrological quantity only when it comes with an operational procedure for estimating it and an uncertainty statement describing the estimator’s error.

This is also where state-space metrology outperforms naive spatial language. A spatial separation does not automatically give a meaningful qubit distance, because orthogonality and distinguishability can be realized without spatial separation and can be destroyed even when spatial separation exists. State-space distances are designed to capture the operational essence, which is why they are the natural foundation for a qubit metrology.

6.4 Tomography, interference, and calibration of state distance

To turn state-space distance into a metrological object, we must be able to estimate it experimentally and attach an uncertainty. There are two main routes: tomography-based estimation and interference-based estimation. Both require calibration.

Tomography-based estimation reconstructs the qubit state from measurements in multiple bases. Operationally, one prepares a state many times, measures along different axes, and uses the resulting statistics to infer the state’s Bloch vector (and thus the density matrix). Once two states are reconstructed, one computes their distance under the chosen metric. The metrological strength of tomography is generality: it does not assume a particular implementation beyond the ability to measure in a set of bases. Its weakness is sensitivity to systematic errors: measurement bias, imperfect basis rotations, and detector drift can distort the reconstructed state.

Interference-based estimation measures overlaps more directly in platforms where coherent recombination is available. In photonics, interference visibility and phase-dependent count rates can be used to infer relative phase and coherence properties, and with appropriate protocols one can estimate quantities closely related to overlap and fidelity without full tomography. The strength here is efficiency and often lower statistical overhead. The weakness is that it can be implementation-specific: the protocol may depend on the ability to interfere the relevant modes cleanly and to control phase precisely.

Calibration is the bridge from “measurement apparatus” to “metrology.” In tomography, calibration means verifying that measurement axes are what you think they are. If you claim to measure along X, Y, and Z, you must calibrate the corresponding rotations and detector mappings. In interference-based protocols, calibration means verifying the phase-to-control mapping, the visibility baseline, and the stability of the interferometer. In both cases, calibration data must be taken and uncertainties propagated into the final state-distance estimate.

A practical metrology also requires separating statistical uncertainty from systematic uncertainty. Statistical uncertainty shrinks with more samples. Systematic uncertainty does not. In qubit experiments, systematic errors often dominate: imperfect pulses, drift in control electronics, detector nonlinearity, polarization leakage, and unmodeled coupling to environment. A state-space metrology must therefore include explicit procedures for estimating and bounding systematics, not merely for collecting more counts.

Finally, a mature state-space metrology should support interoperability. Two labs using different hardware should be able to compare the “distance” between states in the same metric and know what that comparison means. This requires agreed definitions, agreed estimation protocols, and agreed reporting templates. The purpose of this section’s conceptual work is to set up exactly that: a definition of qubit distance grounded in distinguishability, paired with experimental estimation paths (tomography and interference) that can be calibrated, audited, and replicated.

With state-space distance established as the primary metrological object, the next section can responsibly introduce meters again. The paper will propose an explicit mapping from state-space angle to a length-like quantity through a calibrated phase-to-length conversion, while emphasizing that this is a mapping for interoperability and reporting—not a claim that Hilbert space literally is physical space.

7. Mapping State Distance into Meters

State-space metrology gives the correct primitive for qubits: distance as distinguishability. Yet there are practical reasons to map that distance into meters. Engineering teams think in path length, delay, phase noise per meter, and thermal drift coefficients. Photonic platforms are naturally built from waveguides and fibers whose dominant perturbations are length-like. Even in non-photonic platforms, control fields and readout chains often reduce to phase accumulation along some effective path in time or space. A “meters representation” of state distance can therefore serve as a common reporting language, provided we are clear that this is a mapping, not an identity. This section provides an explicit conversion from state-space separation (an angle) into a length-like quantity using interferometric phase calibration, then specifies what that mapping does and does not claim.

7.1 Phase-to-length conversion in interferometric hardware

Interferometry is the natural bridge between state-space angles and meters because it provides a direct, calibrated relationship between phase and optical path length. The fundamental link is that phase accumulation is proportional to path length measured in wavelengths.

For a probe field at reference wavelength λ_0 , an optical path difference ΔL_{opt} produces a phase difference

$$\Delta \text{Phase} = (2\pi/\lambda_0) * \Delta L_{\text{opt}}.$$

This is the core metrological conversion. It does not rely on subjective interpretation; it is the operational content of interference fringes. If the probe wavelength is traceable to a frequency standard, then this phase-to-length relationship is SI-traceable as well.

In practical hardware, “phase” is typically the easiest quantity to control and measure precisely. Small changes in path length, refractive index, or applied voltages to phase modulators can produce detectable phase shifts. The hardware therefore acts as a transducer: it converts controlled actuator settings into phase, and phase into a length-like quantity via λ_0 . This is exactly the kind of transduction that metrology thrives on.

Two caveats are essential.

First, the relevant length is often optical path length, not geometric length. In fiber and integrated photonics, refractive index and dispersion mean that ΔL_{opt} is the physically meaningful quantity for phase accumulation. The mapping must be explicit about whether it is in vacuum, in a specified medium, or in terms of effective index.

Second, the conversion is meaningful only over the bandwidth in which the system remains coherent. Phase noise, linewidth, polarization drift, and dispersion all limit the effective coherence length and thus the stability of the inferred length-like quantity. A metrological mapping therefore requires that the interferometric hardware be characterized sufficiently to claim that ΔPhase is being measured reliably.

With these constraints stated, interferometry provides a clean operational bridge: any quantity that can be expressed as an effective phase shift can be expressed as an equivalent length shift at the reference wavelength.

7.2 Defining $d_{\text{qubit_meters}}(\psi, \phi) = (\lambda_0 / (2\pi)) * \theta$

In Section 6, we treated state-space separation as an angle θ between two pure qubit states $|\psi\rangle$ and $|\phi\rangle$. For qubits, θ is not a geometric angle in physical space; it is a measure of distinguishability: states farther apart in θ are more distinguishable, and orthogonal states correspond to maximal separation. This angle is experimentally estimable via tomography or interference-based protocols.

To map this state-space distance into meters, we define

$$d_{\text{qubit_meters}}(\psi, \phi) = (\lambda_0 / (2\pi)) * \theta.$$

This definition uses the interferometric conversion between phase and length. It effectively interprets the state-space angle θ as an equivalent phase shift ΔPhase , then converts that phase into a length using $\lambda_0/(2\pi)$. In other words:

- θ plays the role of an effective phase difference
- $\lambda_0/(2\pi)$ converts that phase-like quantity into meters

The result is a length-like reporting number. It has a clear operational meaning: it is the path-length difference at wavelength λ_0 that would produce the same phase shift as the state-space angular separation θ .

There are two reasons this definition is attractive.

First, it is dimensionally consistent and traceable to a frequency-defined wavelength. If λ_0 is traceable, then $d_{\text{qubit_meters}}$ is traceable, provided θ is estimated with a calibrated protocol.

Second, it makes a clean connection between qubit geometry and the engineering quantities that degrade qubit performance. In many systems, the dominant noise mechanism is phase noise. Phase noise can be reported as equivalent path-length noise. This mapping lets one report qubit “distance” and qubit stability in the same units that characterize the hardware’s dominant perturbations.

This definition is not claiming that the qubit literally moves in space by that amount. It is defining a metrological reporting convention: a translation of state-space separation into an equivalent length scale via a calibrated phase-to-length conversion.

7.3 What this mapping means and what it does not mean

Because “meters” are seductive, it is essential to state explicitly what $d_{\text{qubit_meters}}$ means and what it does not mean.

What it means is this: $d_{\text{qubit_meters}}$ is an equivalent length associated with a state-space separation, defined by a mapping that uses a chosen reference wavelength. It is useful because it puts qubit separation and phase perturbations into a common unit. It can be used to compare control quality, noise sensitivity, and calibration stability across devices that share the same mapping convention.

What it does not mean is that the qubit’s basis states are spatially separated by $d_{\text{qubit_meters}}$ in the laboratory. For an internal qubit (spin or energy levels), the physical spatial separation may be zero. For a path qubit, the physical path difference may be a design parameter unrelated to θ for arbitrary pairs of states. For a time-bin qubit, the delay may be much larger than the

equivalent length assigned by the mapping. The mapping is about equivalence of phase-like separation, not about literal geometry.

It also does not mean that Hilbert space is physical space. The mapping is not an isomorphism between state geometry and spacetime geometry. It is a calibrated conversion intended for reporting, interoperability, and engineering intuition.

A useful way to phrase it is: the mapping treats state-space angle as a “phase budget” and expresses that budget in meters at a reference wavelength. That is the sense in which it is metrological. It remains honest because it does not conflate the mapped units with the underlying ontology.

Finally, the mapping depends on the choice of λ_0 . If the reference wavelength changes, the meter value changes even though the state-space separation θ remains the same. That alone proves the mapping is a reporting convention rather than a fundamental identity. This is not a weakness; it is a reminder to always declare the reference wavelength and the calibration chain.

7.4 Choosing scale factors: standardization versus convention

Once we admit that mapping state distance into meters is a choice, the next question is whether that choice should be standardized. The answer depends on the objective.

If the objective is interoperability, standardization is valuable. One can choose a community reference wavelength or frequency—perhaps corresponding to a common telecom band or a widely used stabilized laser line—so that $d_{\text{qubit_meters}}$ values reported by different labs are directly comparable without conversion. Standardization turns the mapping into a shared language.

If the objective is internal engineering, convention may be sufficient. A lab can choose λ_0 that matches its own hardware platform, minimizing conversion steps and making the mapping directly tied to the device’s dominant perturbations. In that case, the mapping is still metrological as long as λ_0 is stated and traceable, but it is not universal.

The core metrological distinction is therefore:

- Standardization chooses a community-agreed λ_0 to make meter values comparable across contexts.
- Convention allows λ_0 to be chosen for local convenience, but requires explicit declaration to avoid confusion.

In both cases, the mapping should be treated as a reporting layer on top of the primary state-space metric. The underlying “truth” of qubit separation remains θ (or the chosen state-

space distance measure). The meter mapping is a derived quantity designed to connect that truth to the measurement primitives of interferometry.

This distinction also protects the framework from overreach. If a lab chooses λ_0 such that $d_{\text{qubit_meters}}$ takes on extremely small values, this does not imply access to extraordinarily small physical distances. It only reflects the scale factor. Therefore, standardization is not just about convenience; it is also about preventing rhetorical misuse of meters.

7.5 Cross-platform interoperability: comparing qubits across technologies

One of the most practical motivations for this mapping is cross-platform comparison. Different qubit technologies report performance in different native units: superconducting qubits talk in terms of GHz frequencies and nanosecond gates; trapped ions talk in terms of laser phases and motional sidebands; photonics talks in terms of path length, delay, and interference visibility. A shared metrological language can reduce confusion and increase comparability.

The framework proposed here supports interoperability in three steps.

First, distance in state space is estimated using a declared protocol. Each platform can implement tomography or an equivalent calibration procedure in its own native controls, yielding an estimate of θ (or another chosen distance metric) between states of interest.

Second, the platform declares the mapping scale factor λ_0 and the calibration chain that makes λ_0 traceable. In non-photonic platforms, λ_0 can be treated as a reporting reference rather than a physical carrier wavelength, but it must still be declared as the chosen standard for expressing the equivalent length.

Third, the platform reports $d_{\text{qubit_meters}}$ with uncertainty derived from both the state-space estimation uncertainty and the wavelength reference uncertainty. This produces a number that can be compared across platforms as a common language for “how far apart are these two states in an operational sense,” expressed in a length-like unit that connects naturally to phase noise and stability engineering.

The most important caution for interoperability is to avoid mixing two different notions of “distance.” A photonic platform might also report actual physical path separations in the apparatus, which are literal meters. A superconducting platform might have no such notion. The mapping proposed here does not replace platform-native physical parameters; it complements them with a shared derived quantity that is explicitly tagged as “equivalent length for state-space distance.”

In practice, this can improve communication in at least three contexts:

- Comparing the quality of state preparation across labs, expressed as how far a prepared state is from a target state.
- Comparing susceptibility to phase-like noise sources, expressed in length-equivalent units.
- Establishing common reporting templates for qubit calibration and verification, which is a prerequisite for scalable quantum engineering.

By treating the mapping as a declared, traceable reporting layer rather than a metaphysical claim, we can safely use meters as a lingua franca for qubit geometry without collapsing into category errors. This completes the conceptual bridge: qubit distance is defined by distinguishability, estimated by calibrated measurement, and optionally expressed in meters through a traceable phase-to-length conversion.

8. The Planck-Length Temptation: Why L_p Is Not a Laboratory Ruler

The Planck length, L_p , occupies a peculiar place in modern scientific imagination. It is widely treated as a “fundamental pixel size” of nature, a boundary marker for quantum gravity, and a convenient rhetorical unit for claims about ultimate limits. In a paper about information metrology, it therefore appears almost inevitably as a proposed calibration target: if we can define bit or qubit “distance” in meters, why not define it at the smallest meaningful meter scale?

The answer is that metrology is not about naming a scale. Metrology is about realizing a scale. L_p is an extraordinary theoretical scale, but it is not automatically an operational one. The temptation arises because L_p looks like a number in meters, and interferometry converts meters to phase with stunning sensitivity. Yet the framework developed in this paper draws a bright line between declared scales and operational scales. L_p sits on the declared side for essentially all present-day laboratory contexts, and the reasons are not merely practical inconveniences. They are structural: in ordinary experiments, L_p is not a “small but reachable” distance. It is effectively indistinguishable from zero, unless one enters a regime where the assumptions that make ordinary metrology possible cease to hold.

8.1 Declared scales versus operational scales

A declared scale is a unit assignment or numerical target that can be written down consistently. One can declare that the distance between 0 and 1 is L_p , or that the separation between two branches of a superposition is L_p , or that one radian of Bloch-sphere distance maps to L_p under

a chosen conversion factor. These declarations can be logically coherent and even conceptually useful.

An operational scale is different. It is a scale that can be instantiated by a procedure that others can reproduce, and whose value can be verified with a traceable calibration chain and an uncertainty budget. The chain must have a physical anchor, an instrument response model, and a stability characterization. This is why the earlier sections emphasized frequency standards, interferometric phase readout, and explicitly stated sources of drift and bias. Without these elements, a number in meters is merely a label.

The crucial point is that the same symbol, “meters,” can hide two different claims. A declared scale claims definitional meaning. An operational scale claims measurable reality. The Planck length is frequently invoked as if it were operational, but in most contexts it is functioning as a declared scale: a theoretically motivated marker of where known descriptions likely fail. That is not a criticism; it is simply a category distinction. The metrological problem arises when declared scales are spoken of as if they were laboratory-ruler targets, because that implies an available calibration chain and test protocol that do not, in fact, exist.

This distinction also clarifies a subtlety in the mapping developed in Section 7. If a lab chooses λ_0 and defines $d_{\text{qubit_meters}} = (\lambda_0 / (2\pi)) \theta$, that is an operational mapping if λ_0 is traceable and θ is experimentally estimated with calibrated procedures. If a lab instead replaces λ_0 with L_p as a scale factor, the mapping becomes a convention unless there is an operational way to realize and verify the implied phase-to-length conversion at that scale. In other words, L_p can appear in a mapping, but its appearance does not automatically confer operational meaning.

8.2 Why L_p collapses to “effectively zero” in ordinary experiments

The most direct reason L_p behaves like zero in ordinary experiments is that our measurement handles are wavelength-limited and wavepacket-width-limited, and both are incomparably larger than L_p .

In interferometric language, a length difference d produces a phase shift $\phi = 2\pi d / \lambda$. If $d = L_p$, then $\phi = 2\pi L_p / \lambda$. For any probe wavelength λ used in contemporary precision measurement, L_p / λ is so tiny that ϕ is effectively zero. The interferometer cannot respond to a phase shift that is far below its noise floor, and even heroic averaging does not help once systematic drifts dominate. Operationally, the device behaves exactly as it would if d were zero.

In wavepacket language, if a state $|0\rangle$ is a localized packet and $|1\rangle$ is the same packet shifted by d , then their overlap depends on d relative to the packet width σ . When d is vastly smaller than σ , the overlap is essentially one. That means the “two states” are not distinct as

quantum states, and no measurement can reliably discriminate them. If the logical encoding depends on displacement, then L_p separation does not support a usable two-state system in any ordinary regime because the encoding itself becomes degenerate. Again, operationally, d behaves like zero.

These are not merely engineering complaints. They reveal a structural fact: most laboratory degrees of freedom are coarse-grained relative to L_p . In that coarse-grained regime, the physical predictions of the apparatus are insensitive to differences at the L_p scale. Calling a parameter “ L_p ” in a design does not change the apparatus’s operational resolution. It only changes the story told about a number that cannot be verified.

This is why Planck-length “separations” often reappear, in practice, as choices of scale factor rather than measured distances. If a quantity is below the resolution of the measurement channel, then the only way it enters the discussion is by convention, inference, or speculation, not by traceable observation.

8.3 The point where metrology forces new physics assumptions

There is a deeper reason L_p is not a laboratory ruler: any attempt to make L_p operational pushes measurement into a regime where the standard assumptions of measurement theory no longer cleanly apply.

Metrology requires a probe and an interaction. To resolve a structure at length scale d , the probe must have comparable resolving power. In wave terms, that means wavelengths comparable to d , or in localization terms, it means preparing states with spatial uncertainty comparable to d . If one insists on $d = L_p$ as an operational target, one is insisting on probes and preparations with Planck-scale structure.

At that point, the experiment is no longer a small perturbation on a background world. The act of measurement cannot be treated as a gentle readout of a pre-existing geometry. Instead, the measurement interaction becomes part of the geometry problem. This is precisely what makes L_p special: it is built from constants that mark the intersection of quantum effects, relativistic causality, and gravitational coupling. Treating “distance” as a passive property at that scale is not guaranteed to be meaningful in the way it is at larger scales.

In the metrological language of this paper, this is the point where the calibration chain breaks conceptually, not merely technologically. The ordinary chain is: clock $\rightarrow$ frequency $\rightarrow$ wavelength $\rightarrow$ phase $\rightarrow$ length. That chain assumes that length can be modeled as a stable external parameter that the phase accumulates over, and that the probe’s presence does not fundamentally change the meaning of the path. Near L_p , the assumptions behind “path,” “phase accumulation,” and “external parameter” become questionable. One may still build theories that attempt to operationalize such measurements, but doing so requires explicitly

declaring new physics assumptions: what replaces the classical notion of spacetime distance, how uncertainty is defined, how measurement back-action is modeled, and what counts as a repeatable realization.

Therefore the correct conclusion is not “ L_p is forbidden,” but “ L_p forces one to specify a different measurement theory.” In other words, a Planck-scale metrology is not an extension of existing calibration practice by better engineering. It is a new metrology framework that would have to be defined alongside whatever theory ultimately governs that regime.

8.4 Implications for claims about “Planck-scale information”

The above points impose a discipline on “Planck-scale information” claims. Such claims come in several forms, and metrology helps separate them.

One class of claims is purely conventional: L_p is used as a symbolic unit to express that something is “fundamental” or “ultimate.” This is legitimate rhetoric, but it should not be mistaken for a measured statement. The metrological responsibility is simply to label it correctly as a declared scale or a theoretical marker.

A second class of claims concerns mapping conventions. One might map state-space angles or entropy units into meters using L_p as a scale factor. This can be internally consistent, but it is not evidence that any laboratory has accessed Planck-scale spatial structure. It is a choice of units in a derived reporting layer. The paper’s framework recommends that such mappings be explicitly flagged as conventions and kept distinct from meter-realized path-length metrology.

A third class of claims asserts operational access: that some device encodes, resolves, or transmits information with Planck-length spatial distinctions. Under the framework developed here, such a claim demands an explicit operational protocol, traceability chain, and uncertainty budget. It must answer: what physical procedure realizes the separation, what measurement verifies it, what noise and drift terms are bounded, and what external standards anchor the claim? In the absence of that structure, the claim is not metrological. It may be speculative, inspirational, or programmatic, but it is not yet a measurement result.

Finally, there is a constructive implication. The Planck-length temptation is not merely a trap; it is a diagnostic. It reveals where language outruns instrumentation, and it motivates clearer reporting. If the community adopts a discipline in which L_p is treated as a declared theoretical scale unless an operational chain is provided, then discourse becomes sharper. Researchers can still explore Planck-adjacent theories, but they will do so without unintentionally borrowing the authority of metrology for claims that remain beyond present realization.

The practical payoff is conceptual hygiene. Bits and qubits can be given metrological definitions that are genuinely realizable today, and Planck-scale talk can be retained where it belongs: as a

theoretical boundary marker, a motivation for new measurement frameworks, and a reminder that unit labels are not the same thing as operational standards.

9. Practical Standard Operating Procedures

A metrology that cannot be implemented is merely philosophy in laboratory clothing. The purpose of this section is therefore deliberately practical: to translate the preceding definitions into standard operating procedures that a competent laboratory can execute, document, and reproduce elsewhere. The guiding design constraints are minimalism and auditability. Minimalism means the reference implementation should not require exotic infrastructure beyond what is typical in precision optics and quantum information laboratories. Auditability means the procedure should generate records that allow an external reviewer to evaluate whether the claimed bit-distance or qubit-distance was actually realized, under what conditions, and with what uncertainty. Where possible, these SOPs are written as modular steps that can be adapted to free-space, fiber, or integrated photonics, while preserving the same metrological logic.

9.1 A minimal reference implementation for bit metrology

The minimal bit metrology implementation is a two-path interferometric device whose optical path-length difference is set and verified to equal $d_{\text{bit}} = \lambda_0/2$, with λ_0 traceable to a frequency reference. The most stripped-down realization is a Mach–Zehnder interferometer with a tunable phase shifter in one arm and stable detection at two output ports.

Preparation and apparatus prerequisites:

- A narrow-linewidth laser serving as the probe field.
- An interferometer with two arms, recombined at a beamsplitter or coupler.
- A controllable phase actuator in one arm (piezo mirror, fiber stretcher, thermo-optic phase shifter, or integrated heater).
- Two detectors at the outputs, or one detector with a known output-port selection scheme.
- Environmental control sufficient to maintain fringe visibility and prevent rapid phase drift during a measurement run.

Procedure outline:

First, establish the wavelength reference. Lock the laser frequency to the chosen reference and record stability diagnostics over the measurement interval. If the laboratory does not have a

primary reference, the SOP still requires documenting whatever reference is used and its expected stability; the metrology is weakened but remains structured.

Second, maximize interferometric visibility. Align or tune polarization and mode matching until the measured fringe visibility exceeds a declared threshold. This threshold should be set high enough to guarantee meaningful readout separation but not so high as to be unattainable in typical environments.

Third, set the bit-distance. Sweep the phase actuator through at least one full fringe while recording output intensities. Identify two operating points separated by a phase shift of π . Define these points as the two bit states (0 and 1) and record the actuator settings that realize them. In effect, the SOP turns " $\lambda/2$ " into an operational setting on a phase actuator that can be returned to and verified.

Fourth, validate distinguishability. Repeatedly prepare state 0 and state 1 (alternating in a known pattern) and record detector outputs. Compute the empirical separation of the output distributions and estimate the single-shot bit error probability under the chosen decision rule. Record the decision threshold used.

Fifth, drift characterization. Over a declared time window, repeat the readout at intervals and quantify drift in the interference operating point. If active stabilization is used to hold the phase, record the servo error signal and residual phase noise. If no stabilization is used, record the measured phase wander and define the acceptable measurement window accordingly.

Output artifacts of the SOP:

- A record of the reference frequency lock status and stability over time.
- Fringe scans with fitted phase-to-actuator conversion.
- Visibility measurement and its drift.
- A table of actuator settings that define 0 and 1 and the measured repeatability of those settings.
- A measured bit error probability under stated conditions.
- A drift and noise record sufficient to bound uncertainty in the realized d_{bit} .

This is "minimal" because it requires no absolute length measurement tool, only relative phase and a traceable wavelength. It is metrological because it yields an auditable record connecting the bit definition to the calibration chain.

9.2 A minimal reference implementation for qubit metrology

The minimal qubit metrology implementation should support two layers: a meter-realized mode qubit (path or time-bin) and a state-space distance estimate grounded in distinguishability. The smallest coherent implementation for many laboratories is a photonic time-bin qubit, because it avoids spatial path sensitivity, but a path qubit can be equally valid if the lab already operates stable interferometers.

Preparation and apparatus prerequisites for a mode qubit:

- A source capable of producing single photons or weak coherent pulses suitable for qubit demonstrations.
- A mechanism to prepare superpositions of two modes: a balanced beamsplitter for path qubits, or an unbalanced interferometer/delay for time-bin qubits.
- A recombination interferometer for measurement in multiple bases (at minimum, the computational basis and one superposition basis).
- Phase control (a tunable phase element) to sweep the relative phase and verify interference.
- Detectors with timing resolution appropriate to the encoding.

Procedure outline:

First, define the mode basis. For path qubits, label the two arms as $|0_mode\rangle$ and $|1_mode\rangle$ and verify that cross-talk is below a declared threshold. For time-bin qubits, define the early and late windows and verify that temporal overlap is negligible under the detector response and pulse width.

Second, calibrate the “meter” parameter. For path qubits, measure and report the optical path-length difference used to construct the interferometer and the stability of that difference. For time-bin qubits, measure and report the delay ΔT and translate it into an equivalent distance under the declared medium model. This establishes the apparatus parameter that is naturally length-like.

Third, verify coherence by interference. Prepare an equal superposition and sweep the relative phase. Record the interference fringe and report visibility. High visibility is the operational indicator that the system behaves as a coherent qubit rather than a classical mixture.

Fourth, estimate state-space distance. Choose one or more pairs of states relevant for metrology, such as prepared state versus target state, or two prepared states that should be

separated by a known control angle. Estimate their separation using tomography or calibrated interference measurements. Report the distance in state space and its uncertainty.

Fifth, if desired, map into meters using the declared λ_0 conversion factor. Only after reporting the primary state-space distance should the mapped $d_{\text{qubit_meters}}$ be computed and reported. The SOP should require that λ_0 and the calibration chain be declared in the report so that others can reproduce the mapping.

Output artifacts of the SOP:

- Evidence that the basis modes are orthogonal within declared tolerances.
- A calibrated measurement of the apparatus parameter (ΔL_{opt} or ΔT) and its stability.
- Interference fringes demonstrating coherence, with visibility and phase noise characterization.
- A state-space distance estimate between chosen states, with uncertainty.
- If reported, a $d_{\text{qubit_meters}}$ value with explicit λ_0 declaration.

This “minimal qubit metrology” is not meant to replace advanced benchmarking suites. It is meant to be the smallest implementation that forces the right discipline: separate apparatus length parameters from state-space geometry, verify coherence operationally, and attach uncertainty to any reported distances.

9.3 Verification checklists and reproducibility criteria

Reproducibility requires that a laboratory’s claim can be checked against a checklist rather than interpreted as narrative. This subsection provides a verification checklist that can be used for both bits and qubits.

Verification checklist for bit metrology:

- Wavelength reference declared (frequency lock method stated).
- Fringe visibility measured and reported above declared minimum.
- Bit-distance realization method described (how π phase separation is identified).
- Decision rule for bit readout stated (threshold definition).
- Empirical bit error probability reported under stated conditions.
- Drift characterization reported over a declared time window.

- Environment conditions declared (temperature range, vibration isolation level, enclosure state).

Verification checklist for qubit metrology:

- Qubit platform declared and encoding specified (path or time-bin or other).
- Basis orthogonality verified and cross-talk bounded.
- Coherence verified by interference; visibility reported.
- Measurement bases calibrated if tomography is used.
- State-space distance metric declared (which distance is reported).
- Estimation protocol stated (tomography or interference-based) with sample sizes.
- Uncertainty statement included with separation of statistical and systematic components.
- If a meter mapping is reported, λ_0 and mapping definition are declared.

Reproducibility criteria:

A result should be considered reproducible if an independent lab can follow the SOP and reproduce the reported distances within the combined uncertainty budgets under comparable environmental constraints. This criterion intentionally shifts the emphasis away from “did you get the same number” and toward “did you report the uncertainty and conditions well enough that agreement can be evaluated.” Without that, two laboratories can disagree forever without knowing whether they are measuring different things or merely suffering unreported systematics.

9.4 Reporting templates: what must be disclosed for comparability

To make cross-lab comparison possible, reports must contain a minimal set of disclosures. This is not bureaucracy; it is the price of interoperability.

For bit metrology, a comparable report must disclose:

- Reference frequency specification and how it was realized.
- The platform (free-space, fiber, integrated) and whether ΔL is geometric or optical path length.
- The realized d_{bit} value and how it was operationally located (fringe scan method).
- Fringe visibility at the operating point and over time.

- Readout method and estimated bit error probability.
- Drift statistics over the declared measurement interval.
- The top three contributors to the uncertainty budget and how they were estimated.

For qubit metrology, a comparable report must disclose:

- Qubit encoding and physical implementation details relevant to coherence.
- Calibration of measurement axes or interferometer phase mapping.
- The chosen state-space distance measure and why it is appropriate.
- The state preparation procedure and target states compared.
- The estimated state-space distance with uncertainty and sample sizes.
- Dominant systematic error sources and how they were bounded.
- If a meter mapping is provided, the mapping definition and reference wavelength.

A useful reporting habit is to include a “metrological identity statement” near the start of the Methods section: a short paragraph that says exactly what the reported “distance” is, how it was realized, what it is traceable to, and what uncertainty means in that context. This prevents downstream misinterpretation, especially when readers are tempted to read meters as literal spatial displacement.

9.5 Suggested benchmarks: stability, drift, fidelity, and auditability

Benchmarks are the bridge between metrology and engineering. A standard that cannot be improved cannot become infrastructure. The benchmarks below are suggested as a minimal common set across labs and platforms.

Stability benchmarks:

- Phase stability over time at the operating point, summarized by a standard deviation over defined averaging windows.
- Fringe visibility stability, reported as mean and drift rate.

Drift benchmarks:

- Drift rate of the phase actuator setting required to maintain the pi condition for bits.
- Drift rate of the relative phase in qubit superpositions under passive operation.
- Temperature coefficient of phase (or equivalent) if measured.

Fidelity and distance benchmarks:

- For bits: empirical bit error probability at a fixed decision threshold, plus a sensitivity curve showing how error changes with threshold perturbations.
- For qubits: fidelity to target states or reported state-space distance to target states, with explicit uncertainty.
- Coherence benchmark: visibility of interference fringes for superposition states, with confidence bounds.

Auditability benchmarks:

- Completeness of the calibration log: lock status, fringe scans, environment records.
- Repeatability of calibration: how closely a lab can return to the same d_bit realization after disassembly or after a defined time interval.
- Independence of results from operator choices: demonstrated by repeated runs with different operators or automated scripts.

A practical benchmark philosophy is to prefer benchmarks that do not depend on proprietary device details. Visibility, phase noise, drift rates, and state-space distances are widely meaningful. They can therefore serve as shared targets for improvement and shared language for comparison.

In summary, this section turns the paper's concepts into a usable discipline. It provides minimal implementations that can be realized now, verification checklists that reduce ambiguity, reporting templates that enable comparability, and benchmarks that encourage progress. If the community adopts even a subset of these SOPs, "information distance" becomes something that can be measured and audited rather than merely asserted.

10. Implications and Applications

A metrology for bits and qubits may sound like a niche concern until one notices that the entire trajectory of modern technology is moving toward systems that must be interoperable across vendors, laboratories, and nations. Classical computing reached maturity not because transistors became perfect, but because interfaces, timing budgets, voltage standards, and error specifications became standardized and auditably testable. Quantum technologies are currently in the pre-standard era: impressive demonstrations exist, but the objects being demonstrated are often not comparable in a strict measurement sense. The framework developed in this paper suggests that a major bottleneck is not only device physics, but language: the field lacks a

shared operational vocabulary for “distance between informational states” that cleanly separates what is realized in hardware from what is defined in state space and what is merely a mapping. The implications of introducing that discipline are broad. They touch networking, sensing, device engineering, and even the philosophical hygiene of how we speak about foundational scales.

10.1 Quantum networking and interoperable hardware standards

Quantum networking is fundamentally an interoperability problem. A network implies heterogeneous nodes and links: different sources, different detectors, different channels, different stabilization strategies, and different error mechanisms. Yet most descriptions of quantum networking remain dominated by abstract protocol language, while real deployments fail or succeed on calibration, drift control, phase noise, mode matching, and reporting discipline. A metrology of bits and qubits supplies missing scaffolding.

In networking, the most immediate use is in defining link-level “qubit quality” metrics that are comparable across vendors. Today, a vendor may report a fidelity number without enough information to interpret it across platforms or across test setups. Under the present framework, a network link could be specified in terms of (a) a declared state-space distance measure to a target set of states, (b) a calibration protocol by which that distance is estimated, and (c) if desired, a meter-mapped representation that ties the link’s state-space performance to a phase-to-length stability requirement. This allows procurement and deployment to move from “trust me” performance claims to auditable, comparable metrics.

The meter-realized approach is particularly natural in photonic networks. Fiber links, interferometers, and integrated photonic circuits are dominated by path-length and phase stability issues. Expressing the required performance as a bound on effective path-length noise or drift immediately connects qubit-level requirements to engineering actions: thermal management, vibration isolation, active phase stabilization, and polarization control. The point is not to reduce quantum networking to classical metrology, but to give the quantum specifications a directly actionable translation into the hardware parameters that network engineers can actually control.

A second implication concerns standard reference devices. A mature networking ecosystem will likely require “traceable qubit reference modules” analogous to classical test instruments. Such a module would implement a mode-encoded qubit with a declared reference wavelength, provide interference-based verification of coherence, output calibrated state preparations, and report distance-to-target in state space with a built-in uncertainty budget. This paper’s SOP framework is an early blueprint for what such reference modules could look like. If adopted, it

could lower barriers to entry and reduce the current fragmentation where every lab's qubit is, in practice, a different species.

Finally, a disciplined distinction between operational and declared scales reduces the risk of exaggerated claims in networking contexts. "Planck-scale timing" rhetoric or "ultimate physical limit" language can creep into marketing and grant proposals. A metrological framework forces the simple question: what is being measured, how is it traceable, and what is the uncertainty? That discipline protects both engineering credibility and the long-term stability of the ecosystem.

10.2 Quantum sensing and the unification of phase and information metrology

Quantum sensing is often described as "using quantum states to measure tiny signals," but in practice it is an art of controlling and reading out phase. Interferometers, atom interferometers, superconducting resonators, and spin ensembles all reduce to phase accumulation under an interaction Hamiltonian. Noise and drift appear as phase diffusion, frequency fluctuations, and dephasing. The framework of this paper aligns naturally with that reality by treating distinguishability as the fundamental quantity and phase-to-length conversion as a natural SI bridge.

One immediate implication is that quantum sensing and information metrology can share a common reporting language. In sensing, a device's performance is often expressed as sensitivity to a parameter (such as acceleration, magnetic field, or refractive index change). Under this paper's framing, the relevant question becomes: how much does the parameter shift the state in state space, and how distinguishable does that shift become under realistic noise? That is already the operational content of sensitivity. By making "state-space distance per unit signal" a reported quantity, and by allowing an equivalent meter mapping when appropriate, one can unify the language of sensing performance with the language of qubit stability.

Another implication is calibration discipline. Many sensing demonstrations are limited not by quantum noise but by systematic drift in phase, temperature coupling, and imperfect control pulses. The SOP and uncertainty-budget structure proposed here applies directly. One can treat the sensing device as a state-preparation-and-measurement chain and demand the same metrological reporting: calibration logs, drift characterization, separation of statistical and systematic uncertainty, and explicit disclosure of environmental sensitivity. This can improve reproducibility across groups and reduce the current gap between impressive laboratory demonstrations and deployable sensor products.

A deeper unification is conceptual: phase is the bridge between physical parameters and information geometry. In quantum sensors, the measured quantity is encoded as a phase shift. In qubits, control and errors are largely phase-like. Treating phase as a metrological primitive

and treating state-space distance as the operational consequence of phase shifts suggests an integrated discipline: “phase and information metrology” as one field rather than two loosely connected communities. The practical benefit is that calibration tools developed for sensing can directly improve qubit engineering, and vice versa.

10.3 Information geometry as an engineering discipline

The phrase “information geometry” is often treated as theoretical, but in a metrological setting it becomes engineering: it tells you how far a system moves in state space under control actions, noise sources, and environmental perturbations. Once a distance measure is operationalized and accompanied by estimation protocols, it becomes a design parameter.

One implication is better control engineering. If a control pulse is intended to rotate a qubit state by a certain angle, then the achieved rotation can be measured as a state-space distance from the target trajectory. That distance can be decomposed into coherent error (wrong axis, wrong angle) and incoherent error (dephasing, amplitude damping), each of which has a different remediation strategy. This decomposition is more actionable than a single scalar fidelity number. It tells engineers whether to improve calibration, reduce noise, or redesign hardware.

Another implication is cross-technology comparability in a meaningful way. Today, different platforms excel under different metrics. Some are strong in coherence time, others in gate speed, others in connectivity. Without a shared metrological framework, comparisons become apples-to-oranges. State-space distance measures provide a platform-neutral primitive: how close is the prepared state to the intended state, and how stable is that closeness over time and environment? Meter mapping then gives an optional translation into engineering units where phase and drift are dominant. This does not erase platform differences; it provides a common language for them.

A third implication is auditability as a design constraint. In safety-critical or infrastructure-grade quantum systems, it will not be enough to claim performance. Performance will have to be demonstrated repeatedly with logs and uncertainty budgets. Treating information geometry as engineering means building systems that can self-report their state-space distances, calibration health, and drift in real time. This moves the field toward “instrumented qubits” analogous to instrumented classical systems that report voltage margins, temperature, and error rates.

Finally, the mapping discipline helps avoid category errors in engineering narratives. Engineers often want a length scale because it feels concrete. The framework allows a length-like quantity to be reported without pretending that state vectors are literally separated in space. That preserves conceptual correctness while satisfying the pragmatic needs of engineering communication.

10.4 Philosophical and foundational implications without overclaiming

Any attempt to assign meters to information will attract metaphysical interpretations: “Is information physical?” “Is Hilbert space real?” “Are bits the substrate of spacetime?” This paper’s framework has philosophical implications, but its virtue is precisely that it lets those implications be discussed without smuggling in empirical claims that the metrology cannot support.

The first implication is epistemic hygiene. The framework forces a discipline of speech: when we say “distance,” we must specify whether we mean spatial separation, optical path length, phase, or distinguishability. Many foundational confusions arise from sliding between these meanings without noticing. By keeping the categories explicit, the framework reduces ambiguity and makes debates more productive. Disagreement can be localized: are we disputing a measurement procedure, a mapping convention, or an ontological claim?

The second implication is a clearer boundary between convention and discovery. Mapping state-space angles into meters is useful, but it is not a discovery about spacetime. It is a reporting layer anchored to a reference wavelength. Once this is understood, one can explore bold ideas (for example, that information geometry has deep ties to physics) while remaining honest about what has been operationally demonstrated. The paper’s critique of Planck-length rhetoric should be read in this spirit: it does not deny that L_p may matter; it denies that invoking L_p automatically creates a metrological claim.

The third implication concerns the meaning of “fundamental limits.” In engineering culture, “limit” language is often used loosely. Metrology insists that limits must be tied to operational procedures and noise models. In quantum contexts, some limits are fundamental (non-orthogonal state discrimination), while others are contingent (thermal drift in a particular interferometer). The framework helps separate these. That separation matters because it prevents the premature sacralization of current engineering obstacles as “fundamental,” and it prevents the opposite error of treating fundamental constraints as merely engineering challenges.

Finally, the framework suggests a measured stance toward “information as geometry.” One can legitimately say: qubit states live in a geometric space whose distances correspond to operational distinguishability. One can even say: this geometry can be mapped into SI units through calibrated phase-to-length conversions for reporting and engineering purposes. What one cannot responsibly say, on that basis alone, is that Hilbert space literally is physical space, or that Planck-scale distances are being accessed. The value of the framework is that it enables strong, high-clarity statements while gently refusing the slide into overclaiming.

In summary, the implications of an information metrology are not confined to the lab bench. They shape how quantum systems become interoperable technologies, how sensing and computation share calibration languages, how engineers design around distance in state space, and how foundational discourse stays honest about what is measured versus what is imagined.

11. Conclusion: Information-as-Measurable-Geometry

The core ambition of this paper has been modest in one sense and radical in another. Modest, because it does not attempt to redefine information theory or to smuggle metaphysics into physics. Radical, because it insists that “information distance” can and should be treated with the same seriousness we apply to voltage standards, frequency references, and length calibration: as something that must be realized, verified, reported with uncertainty, and compared across laboratories. When that discipline is applied, information stops being merely an abstract symbol system and becomes a measurable geometry: a structure whose separations can be operationalized, audited, and engineered. The payoff is not only conceptual clarity but technological acceleration. As quantum systems approach infrastructure scale, the decisive bottleneck will increasingly be comparability: the ability to know that a qubit prepared in one lab is “the same kind of qubit” prepared in another, within declared uncertainty. That is a metrology problem. This conclusion restates the proposed framework, clarifies what becomes visible once “distance” is treated operationally, and sketches the most realistic next steps toward a community standard.

11.1 Restating the two-standard framework

The paper’s main proposal is a two-standard framework for information distance, one standard anchored in SI length and the other anchored in state-space distinguishability.

The first standard is meter-realized. For bits, it uses a calibrated optical path-length difference tied to a traceable reference wavelength. The canonical choice $d_{\text{bit}} = \lambda_0/2$ is operationally attractive because it corresponds to a π phase shift and maximizes interferometric contrast. For qubits, the meter-realized approach uses mode separation (path or time-bin) as a primitive: the apparatus defines orthogonal modes whose separation can be expressed as an optical path-length difference or time delay, and coherence is verified by interference. In both cases, the standard is not “meters by declaration,” but meters by traceability: clock $\rightarrow$ frequency $\rightarrow$ wavelength $\rightarrow$ interferometric phase $\rightarrow$ length, plus an explicit uncertainty budget.

The second standard is state-space realized. For qubits, distance is defined first as distinguishability: an angle on the Bloch sphere for pure states or an appropriate metric for mixed states, estimated via tomography or interference-based protocols. This standard respects what qubits fundamentally are: points in a state space whose geometry is revealed by

measurement statistics. It is metrologically attractive because it is platform-neutral and directly tied to operational tasks: discrimination, fidelity-to-target, and error characterization.

The framework then allows a controlled mapping from state-space distance into meters via a declared reference wavelength, for example $d_{\text{qubit_meters}}(\psi, \phi) = (\lambda_0 / (2\pi)) \cdot \theta$. This mapping is useful, but it is explicitly labeled as a mapping. It is a reporting layer that translates an operational state-space separation into a length-like unit through a calibrated phase-to-length conversion. It is not an ontological claim that Hilbert space is physical space.

Taken together, this two-standard structure solves the central confusion that repeatedly derails discussion: it prevents “distance” from sliding silently between incompatible meanings. If the claim is about apparatus geometry, the meter-realized standard applies. If the claim is about quantum-state separation, the state-space standard applies. If one wishes to translate between them, the mapping is explicit and traceable, rather than implied by metaphor.

11.2 What becomes clearer when “distance” is operationalized

Operationalizing distance produces clarity in four places that matter for real progress: language, engineering, comparability, and claims discipline.

Language becomes sharper because “distance” stops being a free-floating intuition. Once a community adopts a requirement that every “distance” statement must specify its type (spatial displacement, optical path length, phase, or distinguishability) and its measurement protocol, many pseudo-disagreements dissolve. People discover they were talking about different objects. A photonics engineer talking about path drift and a theorist talking about state overlap are not disagreeing; they are using the same word for different distances. Metrology forces the distinction into the open.

Engineering becomes more actionable because state-space geometry can be tied to the real knobs that distort it. The mapped meter representation is especially useful here. Phase noise becomes equivalent path-length noise. Drift coefficients become “distance drift” in a shared unit. Control errors become measurable deviations in state-space distance from a target. This turns “information geometry” from a theoretical ornament into a design discipline: the engineer can identify which perturbations move the system far in state space and which only produce harmless fluctuations.

Comparability becomes realistic because performance claims become structured. Instead of a single headline fidelity number, a lab can report: the distance metric used, how it was estimated, the measurement bases and calibrations, the stability of the reference wavelength, the visibility achieved, and the uncertainty budget. That reporting is not mere paperwork. It is the mechanism by which independent labs can meaningfully compare results and know

whether discrepancies are due to physics, calibration differences, or environment. Comparability is the precondition for a supply chain.

Claims discipline improves because the framework draws a bright boundary between declared scales and operational scales. This is where the Planck-length temptation becomes instructive. In ordinary laboratory contexts, L_p is a declared theoretical boundary marker, not a realizable ruler. Operational metrology forces that fact to be stated plainly. This does not suppress speculative thinking; it protects the credibility of measurement claims by making it clear when a number in meters is an SI-traceable realization and when it is a symbolic or conventional mapping.

Once these clarities are in place, the phrase “information-as-measurable-geometry” stops sounding like a slogan. It becomes a literal statement: information distances can be defined by reproducible procedures, measured with known uncertainty, and used as engineering constraints.

11.3 Future work: standards bodies, reference devices, and shared datasets

If this framework is to matter beyond a single paper, it must land in institutions and artifacts. The most plausible future work is therefore institutional, not merely theoretical.

Standards bodies are the natural next step. Classical technology did not become interoperable because everyone agreed philosophically; it became interoperable because communities codified procedures, reporting formats, and reference implementations. A realistic near-term target is a “quantum information metrology profile” that specifies (a) a small set of agreed distance metrics for qubit comparison, (b) minimal estimation protocols (tomography or validated overlap protocols), (c) required disclosure fields for comparability, and (d) baseline uncertainty-budget structure. This could be pursued in the same spirit as existing measurement standards: voluntary at first, then adopted by procurement and publication norms as the ecosystem matures.

Reference devices are the physical anchor. The field will likely benefit from portable, auditable modules that can act as traveling standards: a meter-realized bit module (interferometric path-length standard with stable wavelength reference) and a minimal qubit module (mode-encoded qubit with calibrated interference visibility and state-space distance estimation). Such devices need not be perfect to be useful; they need to be stable enough, documented enough, and reproducible enough that independent labs can use them to compare and calibrate their own systems. The SOPs in this paper are an initial blueprint for what such reference devices should log and report.

Shared datasets are the third pillar. Metrology thrives on intercomparison campaigns: multiple labs measure the same artifact and report results and uncertainties. Quantum systems can

adopt the same pattern by sharing standardized datasets of measurement outcomes under declared protocols. This enables cross-validation of estimation methods, detection of systematic biases, and benchmarking of reproducibility. A minimal shared dataset program would include raw measurement counts for defined state-preparation-and-measurement tasks, accompanied by full calibration logs and environmental metadata. The goal is not merely to publish “results” but to publish auditable evidence.

Finally, future work should include explicit stress tests for the boundary between operational and declared scales. The community should cultivate a habit of marking which claims are within current calibration reach and which require new physics assumptions. That habit will protect the field as it scales, because it prevents the inflation of rhetoric from outrunning the credibility of measurement.

In closing, the paper argues for a simple maturity move: treat information distance like any other quantity that matters in real systems. Define it operationally. Make it traceable where possible. Attach uncertainty. Separate realization from mapping. And build shared procedures so that “a qubit” is not a private dialect but a comparable, auditable object. If that happens, information will not merely be spoken of geometrically; it will be measured geometrically—one calibrated distance at a time.

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Appendix A. Worked Examples in Meters

A.1 Reference wavelengths and the canonical bit-distance

In the meter-realized bit metrology proposed in this paper, the canonical bit-distance is

$$d_{\text{bit}} = \lambda_0 / 2.$$

Below are concrete values for common reference wavelengths:

- $\lambda_0 = 1550 \text{ nm} = 1.55\text{e-}6 \text{ m}$
 $d_{\text{bit}} = 7.75\text{e-}7 \text{ m} (775 \text{ nm})$
- $\lambda_0 = 1064 \text{ nm} = 1.064\text{e-}6 \text{ m}$
 $d_{\text{bit}} = 5.32\text{e-}7 \text{ m} (532 \text{ nm})$
- $\lambda_0 = 780 \text{ nm} = 7.80\text{e-}7 \text{ m}$
 $d_{\text{bit}} = 3.90\text{e-}7 \text{ m} (390 \text{ nm})$
- $\lambda_0 = 633 \text{ nm} = 6.33\text{e-}7 \text{ m}$
 $d_{\text{bit}} = 3.165\text{e-}7 \text{ m} (316.5 \text{ nm})$

Interpretation: these are not “spatial separations between symbols.” They are optical path-length differences that realize a pi phase shift at the chosen λ_0 , verified interferometrically.

A.2 Phase-to-length conversions: quick calculator

Interferometric hardware provides the conversion

$$\Delta L_{\text{equiv}} = (\lambda_0 / (2\pi)) * \Delta \text{Phase}.$$

For $\lambda_0 = 1550 \text{ nm}$:

- $\lambda_0 / (2\pi) = 1.55\text{e-}6 \text{ m} / 6.283185... = 2.466\text{e-}7 \text{ m} (246.6 \text{ nm}) \text{ per rad}$

So, at 1550 nm:

- 1 rad phase shift corresponds to $2.466\text{e-}7 \text{ m} (246.6 \text{ nm})$
- 0.1 rad corresponds to $2.466\text{e-}8 \text{ m} (24.66 \text{ nm})$
- 0.01 rad corresponds to $2.466\text{e-}9 \text{ m} (2.466 \text{ nm})$
- 1 mrad (0.001 rad) corresponds to $2.466\text{e-}10 \text{ m} (0.2466 \text{ nm})$

For $\lambda_0 = 1064 \text{ nm}$:

- $\lambda_0 / (2\pi) = 1.064\text{e-}6 \text{ m} / 6.283185... = 1.693\text{e-}7 \text{ m} (169.3 \text{ nm}) \text{ per rad}$

These “equivalent lengths” are exactly what an interferometer turns phase control into, and they are the natural units for drift and phase-noise engineering.

A.3 State-space angle to meters mapping examples

This paper proposes the optional reporting map

$$d_{\text{qubit_meters}}(\psi, \phi) = (\lambda_0 / (2\pi)) * \theta$$

where θ is the state-space separation angle (for pure states) and λ_0 is the declared reference wavelength used for the mapping.

Using $\lambda_0 = 1550$ nm:

- $\theta = 0$ gives $d_{\text{qubit_meters}} = 0$ m
- $\theta = \pi/6$ (30 degrees) gives $d_{\text{qubit_meters}} = \lambda_0/12 = 1.2917\text{e-}7$ m (129.17 nm)
- $\theta = \pi/3$ (60 degrees) gives $d_{\text{qubit_meters}} = \lambda_0/6 = 2.5833\text{e-}7$ m (258.33 nm)
- $\theta = \pi/2$ (90 degrees) gives $d_{\text{qubit_meters}} = \lambda_0/4 = 3.875\text{e-}7$ m (387.5 nm)
- $\theta = \pi$ (orthogonal pure states) gives $d_{\text{qubit_meters}} = \lambda_0/2 = 7.75\text{e-}7$ m (775 nm)

Small-angle examples at 1550 nm:

- $\theta = 0.1$ rad gives $d_{\text{qubit_meters}} = 2.466\text{e-}8$ m (24.66 nm)
- $\theta = 0.01$ rad gives $d_{\text{qubit_meters}} = 2.466\text{e-}9$ m (2.466 nm)
- $\theta = 1$ mrad gives $d_{\text{qubit_meters}} = 2.466\text{e-}10$ m (0.2466 nm)

What these numbers mean: they are a length-like representation of a state-space angle, using an interferometric phase-to-length scale factor. They do not claim that the physical basis states are literally separated by these lengths in laboratory space.

A.4 Time-bin qubit separations as meters

Time-bin qubits often define basis states by a delay ΔT between “early” and “late” arrival windows. A natural length-equivalent separation is

$$d_{\text{timebin}} = c * \Delta T \text{ (vacuum propagation)}$$

with $c = 299,792,458$ m/s.

Examples (vacuum-equivalent):

- $\Delta T = 1 \text{ ns} = 1 \times 10^{-9} \text{ s}$
 $d_{\text{timebin}} = 0.299792458 \text{ m}$
- $\Delta T = 100 \text{ ps} = 1 \times 10^{-10} \text{ s}$
 $d_{\text{timebin}} = 0.0299792458 \text{ m}$ (about 3.0 cm)
- $\Delta T = 10 \text{ ps} = 1 \times 10^{-11} \text{ s}$
 $d_{\text{timebin}} = 0.00299792458 \text{ m}$ (about 3.0 mm)

If propagation is in fiber or a waveguide, a common engineering approximation is to divide by an effective index n_{eff} :

$$d_{\text{timebin_medium}} \approx (c / n_{\text{eff}}) * \Delta T.$$

For illustration, if $n_{\text{eff}} = 1.468$ (typical order-of-magnitude for telecom fiber group index):

- $\Delta T = 1 \text{ ns}$
 $d_{\text{timebin_medium}} \approx 0.299792458 / 1.468 = 0.2042 \text{ m}$
- $\Delta T = 100 \text{ ps}$
 $d_{\text{timebin_medium}} \approx 0.02042 \text{ m}$ (about 2.0 cm)

This is why time-bin separations are “easy” to realize in meters: nanosecond-scale delays correspond to decimeter-scale lengths.

A.5 Drift and stability examples expressed as meters

These examples show how to turn stability specs into length-like numbers that can be compared across implementations.

Example A (interferometer phase stability target)

Suppose a path-encoded qubit requires relative phase stability within ± 0.01 rad over the measurement window. Using $\lambda_0 = 1550 \text{ nm}$:

- equivalent length stability = $(\lambda_0 / (2 * \pi)) * 0.01$
- $= 2.466 \times 10^{-7} \text{ m} * 0.01$
- $= 2.466 \times 10^{-9} \text{ m}$ (2.466 nm)

Interpretation: holding phase within 0.01 rad at 1550 nm is equivalent to holding optical path length within a few nanometers.

Example B (mapping a reported state-space “miss” into meters)

Suppose tomography or calibrated interference estimates that a prepared state is separated from a target by $\theta = 0.05$ rad. Using $\lambda_0 = 1064$ nm:

- $\lambda_0/(2\pi) = 1.693\text{e-}7$ m per rad
- $d_{\text{qubit_meters}} = 1.693\text{e-}7 * 0.05$
- $= 8.465\text{e-}9$ m (8.465 nm)

Interpretation: this is a length-like representation of the state-space miss, useful for engineering intuition and for comparing “how tight” different systems are in a common unit.

A.6 Planck-length comparison sanity check

A frequently invoked theoretical scale is the Planck length, approximately

$L_p \approx 1.6\text{e-}35$ m.

Comparisons to keep intuition calibrated:

- 1 nm = $1\text{e-}9$ m is about $6\text{e}25$ times larger than L_p
- 0.2466 nm (the 1 mrad equivalent length at 1550 nm) is about $1.5\text{e}25$ times larger than L_p
- 775 nm ($\lambda_0/2$ at 1550 nm) is about $5\text{e}28$ times larger than L_p
- 0.30 m (a 1 ns time-bin in vacuum) is about $2\text{e}34$ times larger than L_p

Interpretation: if one “declares” a bit or qubit distance to be L_p , that declaration is not automatically connected to any interferometric or timing procedure used in ordinary laboratories. In the operational regimes discussed in this paper, L_p behaves as “effectively zero” because it is far below the resolving power of the relevant measurement channels.

It’s important to separate two very different “sizes” that happen to share units:

1. What we defined ($d_{\text{bit}} = \lambda_0/2$) is an optical path-length difference that produces a π phase shift at a chosen wavelength. It’s a *phase standard expressed in meters*, not a claim that a physical “bit cell” has that geometric size.
2. Lithography “bit size” (in CMOS memory/logic) is about feature dimensions and pitches of gates, lines, vias, etc. Those are *geometric* sizes that set packing density and device behavior.

So the similarity is mostly a coincidence of scale: optical wavelengths (hundreds of nm to a few microns) are naturally in the same range as many nanofabricated features.

Where it *does* become interesting (and practical) is integrated photonics:

- Waveguides, couplers, and interferometers are routinely built with hundreds-of-nm to micron-scale geometry, so defining a phase standard using $\lambda/2$ feels “native” to the fabrication toolkit.
- A differential path of ~ 0.8 microns (for 1550 nm) is trivial to draw on a mask — but holding the relative phase stable is not trivial, because temperature and index fluctuations can move you by many radians unless you stabilize or continuously recalibrate.

In other words: lithography can make structures at that scale easily; metrology is about maintaining and verifying the phase condition at that scale over time. The “bit distance” here is a *calibrated phase separation rendered as meters*, not the minimum feature size or the physical footprint of a stored bit.

